FUTURE DIRECTIONS

IN

ANTENNA ANALYSIS AND DESIGN

SOFTWARE

A survey conducted by the Technical Working Group on Antennas (TWGA)

of the

Electromagnetic Code Consortium (EMCC)

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Executive Summary

In March of 2000, the Technical Working Group on Antennas (TWGA) of the Electromagnetic Code Consortium (EMCC) undertook the task of determining the near-term (three-to-five year) needs of the antenna community for antenna analysis and design software. This report is a description of the effort and its outcome.

The importance of antennas to the Department of Defense (DoD) and other governmental agencies can hardly be overstated. Technological progress along several fronts is bringing within reach antenna designs that were not possible before. Examples are: skin embedded antenna arrays, structurally embedded arrays (where parts of the antenna array are also structural members of the array platform), broadband arrays, reconfigurable antennas, etc.

Exploratory studies in such systems clearly indicate that traditional antenna design methods are not sufficient to address the complexity of these systems. We need to resort to rather sophisticated computational electromagnetics (CEM) tools, tools that are specifically tuned to antenna analysis and design, if we are to succeed at all.

With this in mind, the TWGA of the EMCC embarked on an effort to determine the kinds of tools that the ideal antenna computational electromagnetics (ACEM) toolbox should contain. As a first step, we compiled a wish list of our own for such a toolbox. We also compiled a list of names of antenna design and antenna software engineers to whom we sent our toolbox statement. Along with it, we sent a survey asking them to evaluate the toolbox and make suggestions of their own. The preliminary toolbox and the questionnaire appear in Section 2 of this report.

In Sections 3 through 8, we discuss the results of the survey. Based on these results, we present a revised form of the antenna analysis and design software toolbox in Section 9. We also describe there what the antenna community sees as the major areas of research in ACEM for the next three to five years. In addition, in Section 10 we propose a number of databases that may facilitate antenna analysis and design.

For those not familiar with the EMCC and its objectives, we invite them to visit its site at www.asc.hpc.mil/emcc/. All questions on this report should be directed to its author asvestasjs@navair.navy.mil.

We hope you will find the time to leaf through the report. We are aware that it is not easy to persuade government agencies to fund antenna software projects unless there is a dire need for it in some high-priority project. We believe, however, that the kinds of software we are proposing are the tools that will enable the creation of the next generation of advanced antenna systems.

Table of Contents

Table of Figures

Table of Tables

List of Acronyms

ACEM: Antenna Computational ElectroMagnetics
AFOSR: Air Force Office of Scientific Research
AFRL: Air Force Research Laboratory
AIM: Adaptive Integral Method
AP(S): Antennas and Propagation (Society)
ARL: Army Research Laboratory
ARO: Army Research Office
AWE: Asymptotic Waveform Evaluation
BOR: Body of Revolution
CAD: Computer Aided Design
CEM: Computational ElectroMagnetics
CFD: Computational Fluid Dynamics
CHSSI: Common HPC Software Support Initiative
CM: CounterMeasures
CPU: Central Processing Unit
DARPA: Defense Advanced Research Projects Agency
DF: Direction Finding
DoD: Department of Defense
DoE: Department of Energy
DoT: Department of Transportation
DXF: Drawing eXchange Format
ECM: Electronic CounterMeasures
EM: ElectroMagnetic(s)
EMC: ElectroMagnetic Compatibility
EMI: ElectroMagnetic Interference
EMCC: ElectroMagnetic Code Consortium
ESM: Electronic Support (or Surveillance) Measures
EW: Electronic Warfare
FAQ: Frequently Asked Questions
FDTD: Finite Difference Time Domain
FE(M): Finite Element (Method)
FMM: Fast Multipole Method
FSDS: Fast Spectral Domain Solver
GEC: Government Executive Committee (of the EMCC)
GMTI: Ground Moving Target Indicator
GO: Geometric Optics
GPS: Ground Positioning System
GTD: Geometric Theory of Diffraction
GUI: Graphical User Interface
HF: High Frequency (wavelength small as compared to the dimensions of a given structure)
HF: High Frequency (3 – 30 MHz band)
HPC: High Performance Computing
HPCMO: HPC Modernization Office

IGES: Initial Graphics Exchange Specification
ISR: Intelligence, Surveillance, Reconnaissance
JSC: Joint Spectrum Center
LO: Low Observable
MBPE: Model Based Parameter Estimation
MF: Middle Frequency (0.3 – 3 MHz)
MoM: Method of Moments
NASA: National Aeronautics and Space Administration
NAVAIR: NAVal AIR systems command
NAVSEA: NAVal SEA systems command
NAWC: Naval Air Warfare Center
NRL: Naval Research Laboratory
NSF: National Science Foundation
NSWC: Naval Surface Weapons Center
NURBS: Non-Uniform Rational B-Splines
ONR: Office of Naval Research
OSD: Office of the Secretary of Defense
PET: Program Environment and Training
PMA: Program Manager Air (a Navy title)
PO: Physical Optics
PWS: Piece-Wise Sinusoidal
R&D: Research and Development
RCS: Radar Cross Section
RF: Radio Frequency
SAR: Synthetic Aperture (Array) Radar
SATCOM: SATellite COMmunications
SIE: Surface Integral Equation
SIGINT: SIGnals INTelligence
TWGA: Technical Working Group on Antennas
UHF: Ultra High Frequency
UTD: Uniform Theory of Diffraction
VHF: Very High Frequency
VIE: Volume Integral Equation
WPAFB: Wright-Patterson Air Force Base

Section 1. Introduction

In March of 2000, the Technical Working Group on Antennas (TWGA) of the Electromagnetic Code Consortium (EMCC) undertook the task of determining the near-term (three-to-five year) needs of the antenna community for antenna analysis and design software. This report is a description of the effort and its outcome.

The importance of antennas to the Department of Defense (DoD) and other governmental agencies can hardly be overstated. All we have to consider is the number and variety of antennas on a military aircraft or ship to realize the importance of this sensor to the defense community. On the non-military side, the number of commercial products that require antennas is increasing steadily, with applications ranging from traditional ones to entertainment (satellite TV), mobile communications, medical imaging and non-destructive testing, to mention a few.

What concerns us here, however, is not the proliferation of antenna uses but the future of antenna design vis-à-vis DoD needs and requirements. These requirements stem from technological progress along several fronts, with the result that antenna designs that were not possible before are now within reach. Examples are: skin embedded antenna arrays, structurally embedded arrays (where parts of the antenna array are also structural members of the array platform), broadband arrays, reconfigurable antennas, etc. These type of antenna arrays are structurally, materially and geometrically very complex; moreover, they cannot be designed without taking into consideration the surrounding environment, i.e., the platform they are mounted on and any other antennas on it.

Exploratory studies in modern antenna systems clearly indicate that traditional antenna design methods are not sufficient to address the complexity of these systems. We need to resort to rather sophisticated CEM tools, tools that are specifically tuned to antenna analysis and design, if we are to succeed at all.

With this in mind, the TWGA of the EMCC embarked on an effort to determine the kinds of tools that the ideal antenna computational electromagnetics (ACEM) toolbox should contain. As a first step, we compiled a wish list of our own for such a toolbox. We called this the "Antenna and antenna-platform interaction software toolbox". We also compiled a list of names of antenna design and antenna software engineers to whom we sent our toolbox statement. Along with it, we sent a survey asking them to evaluate the toolbox and make suggestions of their own. Both our toolbox and the survey form are discussed in Section 2 of this report. In Section 3, we present some statistics about the participants to our survey and about their organizations. In Sections 4, 5, 6, 7 and 8, we analyze the results of the survey. Based on these, in Section 9 we propose a revised (and final) "Antenna and antenna-platform interaction software toolbox". We also present some near-term research directions and some action items for the EMCC. We conclude this report with Section 10, where we present some ideas about creating databases that may make the antenna designer's task easier.

Most pages of this report are filled with quotations from answers to our survey. We have attempted to create the atmosphere of a round-table discussion, hoping that this will make the report more readable. Quotations from participants appear within double-line frames. We tried to use most of the answers we received. Since it is impossible to avoid mistakes, especially when cutting and pasting, we have included the raw answers to our questions in a number of appendices.

We thank all participants to our survey for taking the time to respond to it and for their thoughtful and thought-provoking comments. Their input to this undertaking is invaluable, and this report is as much their effort as ours.

In terms of lessons learned, if we were to do this again, we would add a number of quantitative questions. There is no substitute for qualitative questions, where people can take all the space they need to tell you what they really think about an issue. If the sample becomes large, however, then there is the problem of how to compile the answers. Fortunately, in this case the number of participants was just right. If a question can be formulated successfully in a quantitative way, then it should be so used; otherwise, it should be stated qualitatively. As to the frequency of this survey, certainly, we should not let more than five years elapse before the next one.

For those not familiar with the EMCC and its objectives, we invite them to visit its site at www.asc.hpc.mil/emcc/.

We close by hoping that this does not become just another report of yet another committee. We are aware that it is not easy to persuade government agencies to fund antenna software projects unless there is a dire need for it in some high-priority project. We believe, however, that the kinds of software we are proposing are the tools without which no advanced antenna system can materialize. We hope that this report will provide people in the right places with sufficient ammunition to make a case for independent (from other projects) development of ACEM software.

Section 2. Preliminary Antenna Design Toolbox and Survey

In March of 2000, the TWGA of the EMCC sent to a select group of antenna designers and antenna design software engineers two documents. One was TWGA's own version of an antenna-design software toolbox (referred to as the TWGA toolbox), while the other was a questionnaire (or survey). The toolbox is presented below, in the space between the dotted lines, in the exact form that it was sent out.

ANTENNA AND ANTENNA-PLATFORM INTERACTION SOFTWARE TOOLBOX

The Government Executive Committee (GEC) of the Electromagnetic Code Consortium (EMCC) believes that the next natural step in the evolution of CEM software is the creation of codes that significantly contribute to antenna design and antenna-platform interaction issues. To this end, the GEC Technical Working Group on Antennas developed a set of requirements and desirable features for such codes, described below. In a separate attachment, we include a questionnaire for you to complete at your earliest convenience. This request is made because of your substantial involvement with the subject matter.

Your input is critical to us. Once we collect this information, we will disseminate it to appropriate funding agencies within the Federal Government in hopes of influencing funding in this area along the directions suggested by the findings. We will also post the results in the EMCC's web site for all to see. An e-mail alert will be sent to the survey's participants.

I. ANTENNA DESIGN TOOLS

A. Software needed to design/compute

1. Wire type antennas (dipoles, Yagis, etc.).
2. Plate (patch) type antennas (notches, reflectors, etc.).
3. Wire-plate type of antennas (short backfires, corner reflectors, etc.).
4. Wideband radiators (spirals, flared notches, etc.).
5. Antennas (wire, plate, slot) in layered media (including dielectric layers, R-cards, FSS layers, photonic materials).
6. Antenna arrays (linear and otherwise) made of elements as above, especially conformal arrays.

B. Such codes should have the ability to

1. Use the latest numerical algorithms for speed and accuracy.
2. Optimize quantities of interest with respect to geometry and materials. Trade-off (Pareto) optimization is desirable.
3. Accurately model feeds, loads (lumped and distributed), etc.
4. Accurately model complex materials (including lossy conductors and dielectrics, R-cards, FSSs, photonic materials, micro-electromechanical systems (MEMS), etc.).
5. Take advantage of planar and rotational symmetries.

6. Compute Sommerfeld integrals for a lossy ground.
7. Store impedance matrix of a structure for later use in a geometrical arrangement that involves this structure in addition to another (numerical Green's function in NEC).
8. Compute all quantities of interest (input impedance, gain, embedded element patterns, array scan impedance, array patterns, etc.).
9. Accurately compute all mutual-coupling effects.

C. They should also

1. Generate geometry or accept geometry in a number of formats.
2. Post-process results efficiently and effectively.
3. Run on several platforms and on parallel as well as sequential architectures.
4. For a specific platform, provide a GUI that will guide and warn the user on every aspect of the input process.
5. Include specific examples (input files) with the code to verify correct installation and function of the software, and provide illustrations of special features in the code.
6. Contain high-quality documentation in electronic form.

D. Possible types of codes include

1. Wire-type method of moments (MoM) codes (e.g., NEC) for use with wire-type antennas.
2. Patch-type MoM codes (e.g., PATCH) for use with antennas that are best modeled using patches.
3. Wire-patch MoM codes (e.g., EIGER, WIPL) for use with antennas that are best modeled using both wires and patches.
4. Finite-element (FE) or finite-difference (FD) codes for antennas in layered media.

II. ANTENNA-PLATFORM AND ANTENNA-TO-ANTENNA INTERACTION TOOLS

A. It is well known that the electromagnetic characteristics of an antenna can be greatly altered by the platform it is mounted on. Since most antennas are add-ons to a platform (rather than having been designed for a particular platform and a specific location on it), then it is necessary to have appropriate software to compute the interaction of the antenna with the platform, as well as with other, neighboring antennas. If the platform is electrically small, we can accomplish this with a MoM code. This is done today for simple antennas. If the platform is large, however, then we need a *hybrid* code. The antenna and its environment will be modeled by an exact code, while the rest of the structure by a HF code. How the two will interact and how many times the results must be iterated (if at all) is a question that requires substantial research effort. This is especially true when there is more than one antenna present.

B. In the future, we will see platforms with antennas structurally integrated in them. The region in which these antennas will reside will have the general shape of a cavity and will be complex, both geometrically and materially. A FE-type code comes to mind (because of the cavity) coupled to the outside through a MoM code (if platform is small) or a MoM/HF code if platform is large. Since the antenna will be an integral part of the platform, we have the opportunity to design it *in situ*, that is, considering the whole platform from the outset.

C. The codes we have sketched here will be of the same kind as those used to design antennas. The principal difference will be in coupling together codes that are based on different methods. As we just indicated, we may have to integrate three codes to account for the properties of a structurally integrated antenna.

D. We are not quite certain we should encourage development of interaction codes that are based strictly on HF methods. These codes may produce good results for simple antennas or with antennas with a simple pattern that is analytically known. But for complex antenna structures or patterns (e.g., one with low sidelobes), we must resort to some exact method to determine them. This brings us back to using a hybrid code.

Besides our own work on this toolbox, we also received inputs from other colleagues, mostly from inside the Government. We gratefully acknowledge their contribution.

We basically divided the toolbox into two parts, one for antenna analysis and design in free space and, the other, for antenna analysis and design with the antenna mounted on its platform and, possibly, in the presence of other antennas.

We point out two important things about this document to dispel some wrong impressions we created unwittingly. The first is that the list of items is *not* prioritized. The second is that the toolbox does not contain one code that does it all. Indeed, as its name implies, the toolbox should contain a multiplicity of tools. These tools might share a lot in common and may even communicate with one another. Each, however, would be designed to perform specific tasks, as, for example, work efficiently with one or more classes of radiators.

The second document we e-mailed out was a survey. We present it here, in the space between the dotted lines.

SURVEY OF ANTENNA DESIGN AND ANTENNA-PLATFORM INTERACTION SOFTWARE REQUIREMENTS

Please return the completed survey to asvestasjs@navair.navy.mil

I. PERSONAL INFORMATION
Name (Optional):
Organization and Address (Optional):

E-mail (Optional): Phone (Optional):
Type of Organization:
Academic Consulting Governmental Industrial

Capabilities of your organization in antenna computational electromagnetics (ACEM). Please check all that apply:
ACEM engine algorithm development

ACEM GUI development
Grid generation
Pre- and/or post-processing
Other (please specify):

Your principal function in reference to antenna computational electromagnetics (ACEM). Please check all that apply and provide number of years inside the parentheses:
Analysis and algorithm development (   )
Antenna design (….)
Antenna software development with extensive experience in antennas (….)
Antenna software development with little experience in antennas (….)
Contract monitoring (….)
Other (   ) (please describe):

If you are an end-user of ACEM software, how often do you use it?
Daily
Weekly
Monthly

Finally, if you know someone in your organization who should be participating in this survey (especially an end-user), please send an e-mail with name, organization, e-mail address and phone number to asvestasjs@navair.navy.mil.

II. ANTENNA AND ANTENNA-PLATFORM INTERACTION SOFTWARE TOOLBOX
Please give your reactions to the accompanying document bearing this title (open antenna_map.doc). Suggest modifications, additions, and deletions. When appropriate, refer to the sections and subsections there. Use additional space if necessary.

III. Please list by name and critique ACEM software you have developed or you are using. Suggest enhancements along the lines of II above. If software is of the "home-grown" variety, please supply a short description mentioning the type of computational engine they use and the kinds of antennas you design with them.

IV. Please give us your thoughts on what the principal thrust of ACEM research should be for the next three to five years.

V. What areas of your business/research/technology does ACEM impact and to what degree? Please help us make a case for you. The EMCC will only make suggestions to the Government. It will not be involved on how contracts will be given out or in their management. The more information you provide, the better for all concerned.

VI. Finally, please suggest appropriate funding agencies for this effort.

The survey is self-explanatory. Nevertheless, we proceed to summarize it here. We designed the first part to be statistical in nature, so as to get a better feeling about the participants and their organizations. In the second, we asked them to use the TWGA toolbox as a starting point for expressing their own thoughts as to what the ultimate toolbox should contain. In the third part, we asked them to talk about their experiences with antenna software they had being using, whether their own or others'. In the fourth, we tried to find out what their ACEM priorities are near-term. In the fifth, we wanted to know the kind of impact ACEM has on their immediate professional environment. In the sixth, and last, we asked them what they considered as appropriate funding agencies for supporting the development of an antenna software design toolbox.

We will present the answers we received in the following sections.

Section 3. Statistics of Survey Participants

In this section, we analyze the responses to Part I of the survey form. The raw data are displayed in Appendix A. Twenty-eight people participated in the survey. The distribution is shown in Fig. 3.1. Government dominated with twelve respondents, followed by Academia with nine, Industry with five, and Consulting with two. Certainly, the distribution is not what we expected. We would have welcomed a much greater participation from the industrial/consulting community since they know best what is needed in an ACEM toolbox and, also, since they will be the principal beneficiaries of any product that may result from this effort.

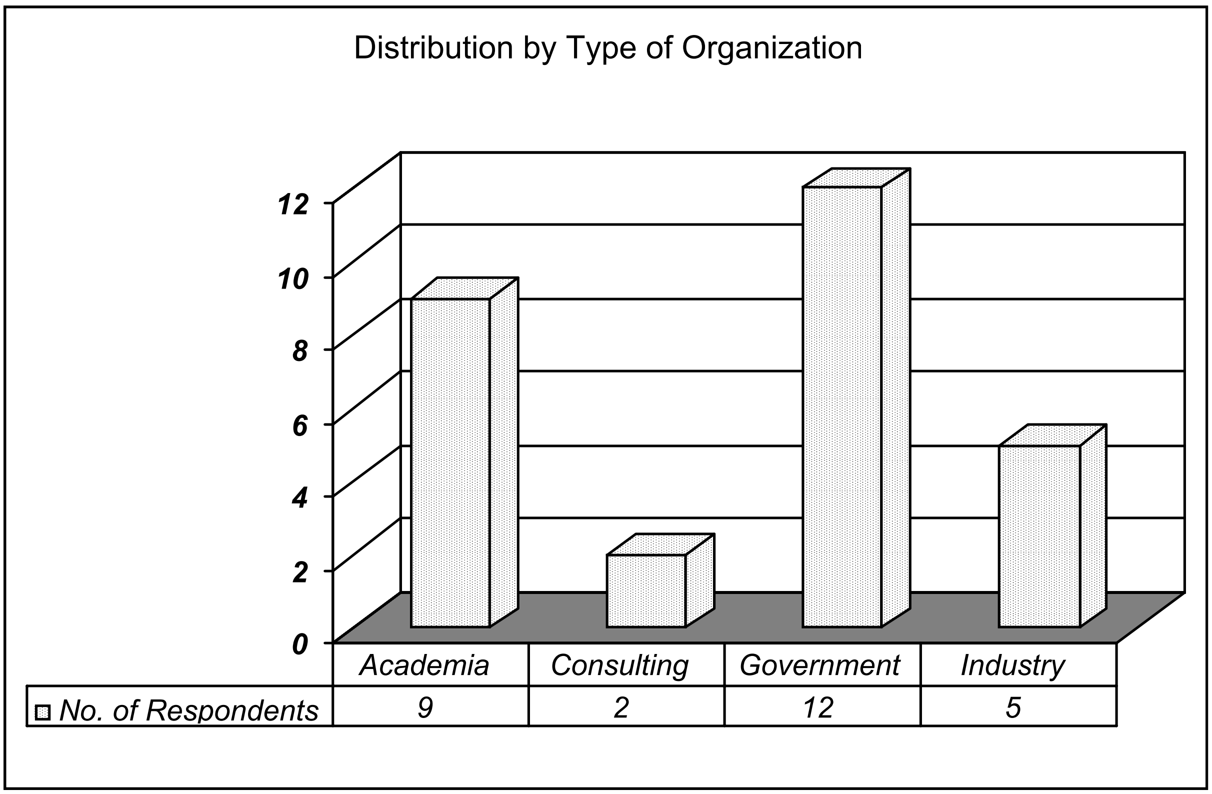

Figure 3.1. Distribution of survey participants by organizational affiliation.

The capabilities of each participant's immediate workplace are summarized in Fig. 3.2. The largest concentration is in algorithm development, followed by pre- and post-processing, GUI development, and grid generation. The column "other" represents a variety of capabilities; specifically: "using existing codes", "utilizing available commercial software", "antenna, radar, and FSS design", "geometry pre-processing (software development and services)", "antenna design, fabrication and testing", "fast, efficient and accurate complex full matrix solvers", "modeling and analysis using a variety of ACEM codes", and "antenna design, FSS, microwave circuits etc.".

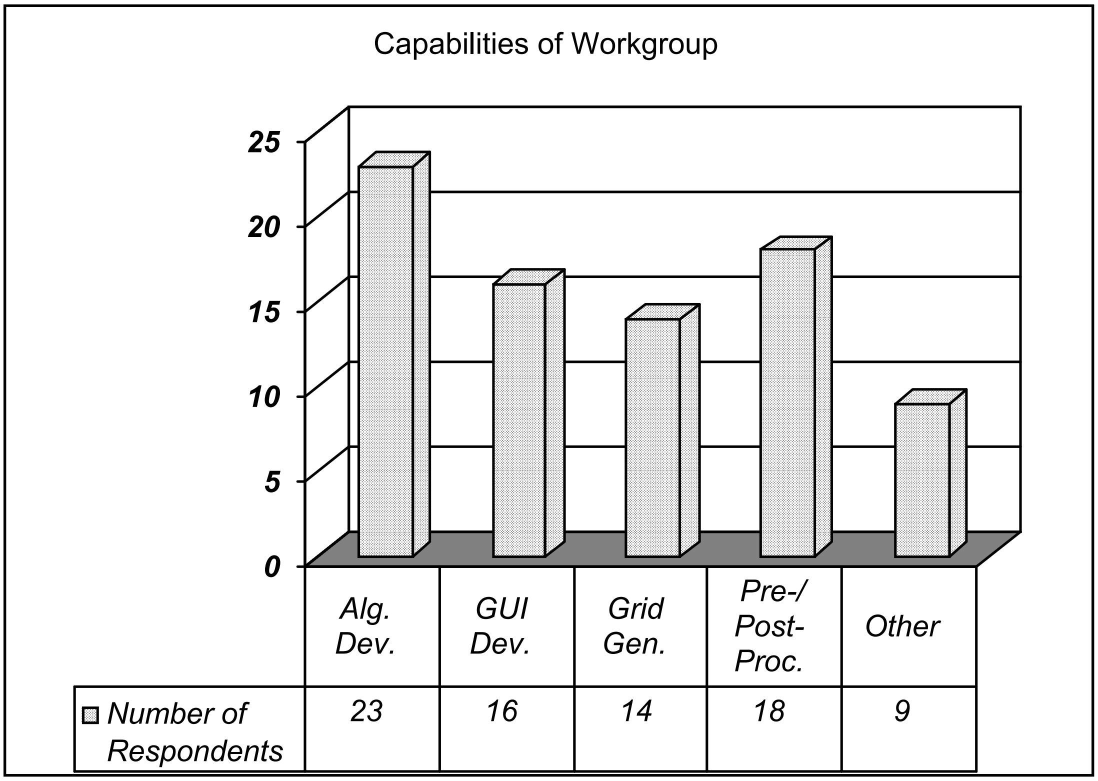

Figure 3.2. Workgroup capabilities for each participant.

These results are further broken down in Figs. 3.2.1 to 3.2.3, where capabilities are presented by type of organization. Consulting and Industry have been merged into one group. In the academic and government groups, algorithm development dominates. This is predictable since algorithm development is the research-intensive side of ACEM, something usually done in universities and government research laboratories. Activities are more evenly distributed in the Consulting / Industrial group. There, the concern appears to be more on how to turn algorithms into user-friendly computational tools rather than just algorithm generation. Thus, we see an equal effort toward GUI development and pre- and post-processing capability.

From Fig. 3.2, it becomes apparent what is already well known in the CEM community, namely, that the weak link in CEM and ACEM is grid generation. Although there is a proliferation of CAD packages tuned to grid generation for structural, mechanical, thermal, CFD, etc., analysis and design (some complete with computational engines), there is virtually no counterpart for CEM. Moreover, the form of the grid in CEM and ACEM is very much dependent on the numerical method used to address the electromagnetic problem. Thus, creating a universal grid generator is not a simple matter. This is one of the issues that deserve serious consideration by the community. Without a good grid generator, properly tuned to the electromagnetic computational engine, a CEM/ACEM code is of little use.

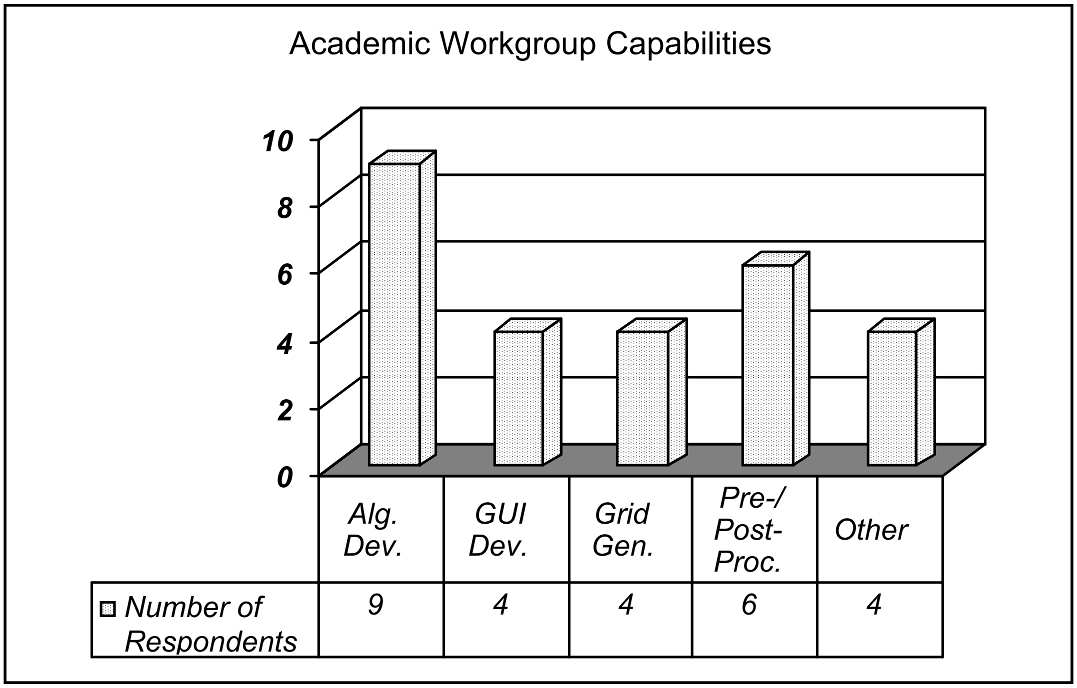

Figure 3.2.1. Academic workgroup capabilities.

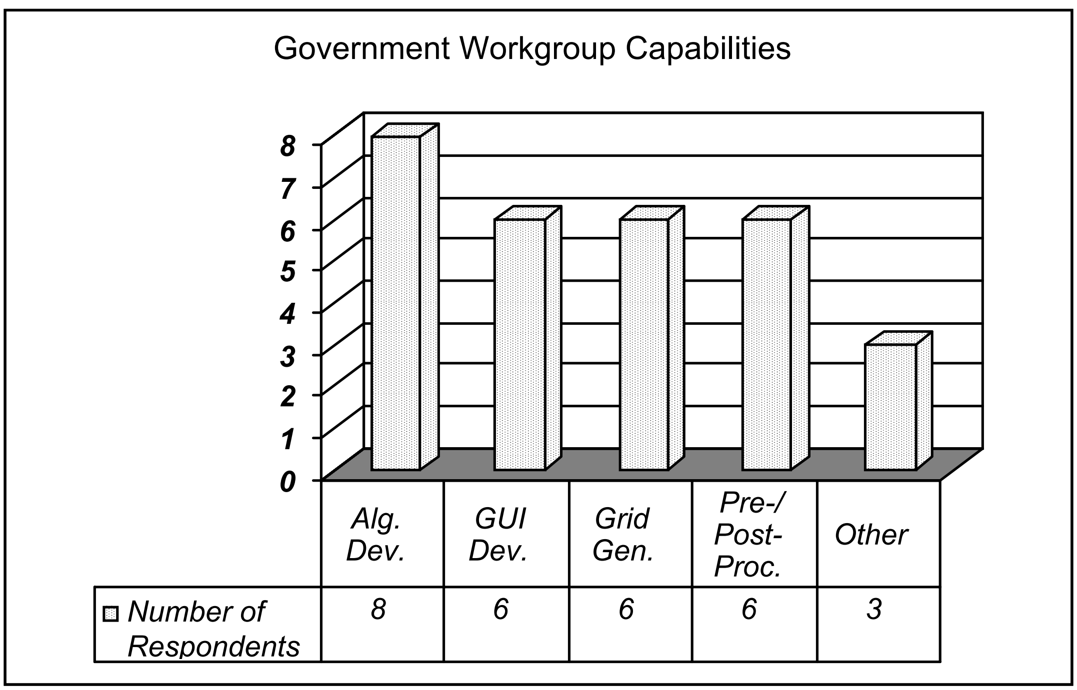

Figure 3.2.2. Government workgroup capabilities.

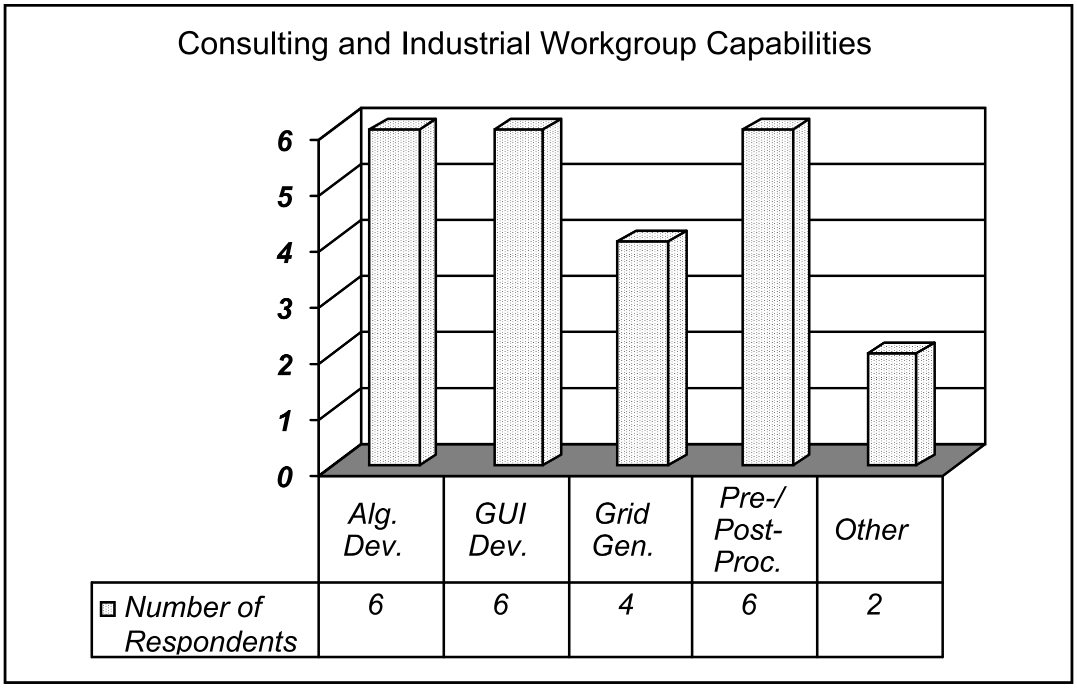

Figure 3.2.3. Consulting/Industrial group capabilities.

Figure 3.3 displays a participant's expertise and years of experience. It is clear from the chart that we are dealing with an experienced and knowledgeable group of people. Those involved in analysis and algorithm development, antenna design, and antenna software development with extensive antenna experience average twenty years at these activities. *These numbers spread across all organizational groups and make the results of this survey so much more credible.*

Figure 3.4 shows the frequency of use of ACEM software in the end-user group. Out of twenty-eight survey participants, eighteen reported that they are end users of ACEM software. Of these, ten are daily users, six weekly, and two monthly. Table 3.1 shows the distribution among the three organizational groups. Out of the eighteen participants, ten are government, five academia, and only three from consulting/industry. The statistical sample, however, is so small that we should not try to draw any conclusions from these figures. The only thing we can say is that, of the twenty-eight participants, sixteen are regular users of ACEM software.

In conclusion, the participants of this survey are highly qualified experts in antennas and antenna design software. A number of them are at the forefront of ACEM software development while others have many years of antenna design experience, as many as forty-eight on one occasion! We think they deserve to be heard.

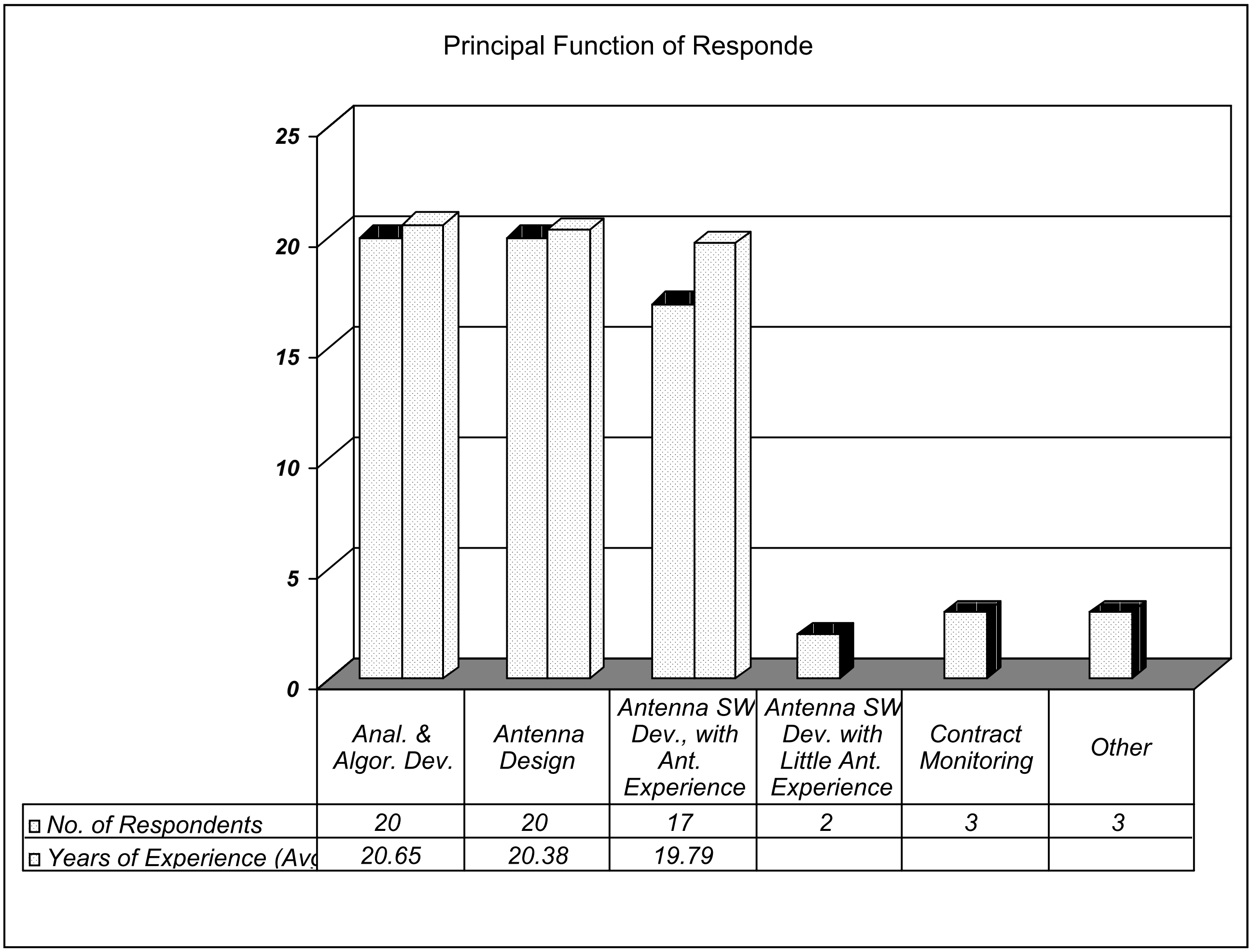

Figure 3.3. Principal function of survey participants and average years of experience in that function for the group.

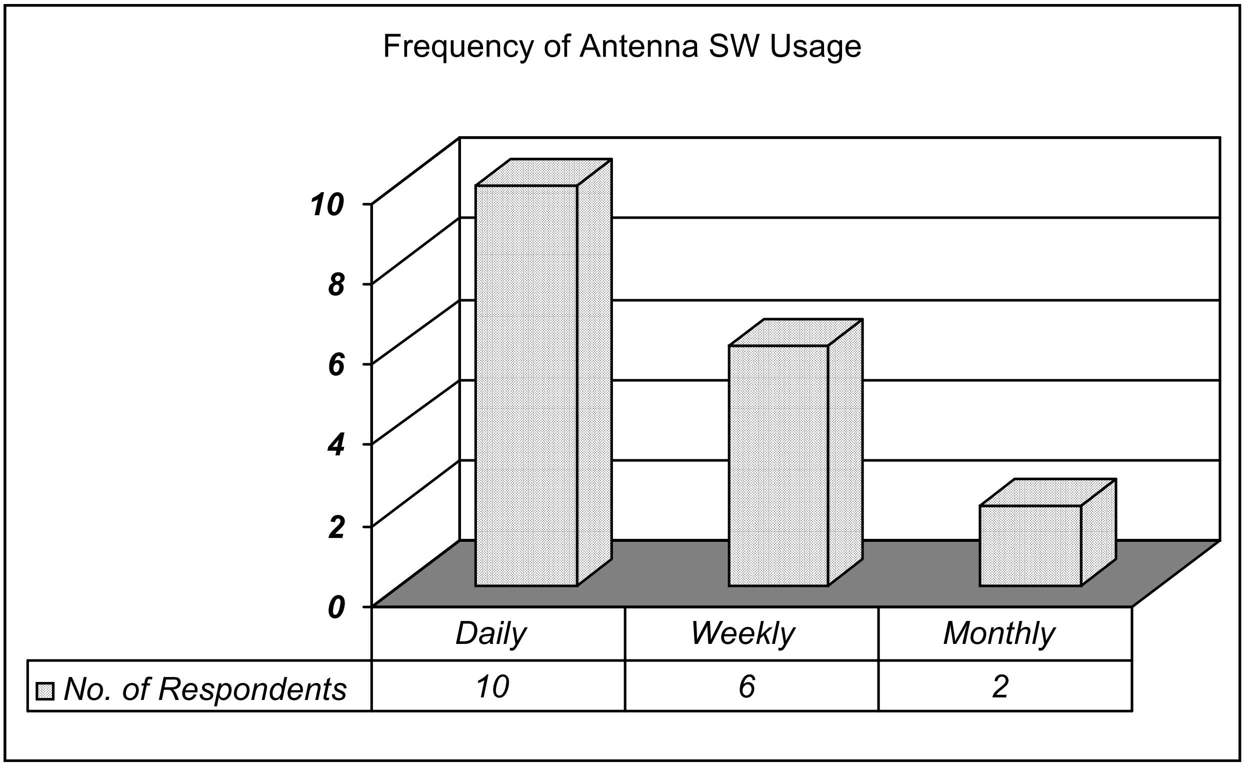

Figure 3.4. Frequency of use of ACEM software among end-users.

Table 3.1. Frequency of use of ACEM software among the three groups.

	Daily	Weekly	Monthly
Academia	2	2	1
Government	5	4	1
Consulting/Industry	3	0	0

Section 4. Part II of the Survey: Reactions to Preliminary Toolbox

In Part II of the survey, the participants were asked to give their reactions to the preliminary antenna software toolbox, and to suggest modifications, additions, and deletions.

The responses can be found in raw form in Appendix B. It is appropriate to begin with a quote from a participant who has been in the antenna "business" for almost half-a-century,

> "I have mixed feelings about CEM design codes, based on many years of experience with them and the more than a thousand Fortran codes I have prepared and used… General purpose codes do not work well for a variety of free standing antennas…It is much more effective to have codes where each does a specific kind of antenna... And of course can be hybridized with a body code…Thus I believe the EMCC should have an effort focused in two directions. The first is the hybrid type codes that include body interactions. The second would be codes for free standing antennas where the codes are accurate, easy to use, and well documented."

These words summarize very well what the antenna software toolbox should be about. With this in mind, we proceed to look at a good part of the responses and, along the way, offer some commentary.

The coupling (interaction) of antennas within one another and their platform is one of the most recurring themes. Here are two characteristic responses,

> "Mutual coupling between antenna elements within the same array is predicted efficiently for infinitely large arrays. There is a deficiency in this area for large finite arrays, especially when embedded in media. Mutual coupling is also a serious RF system issue wrt EMC/EMI. Predicting antenna coupling, radiation patterns, RCS when installed on some platform is a capability that is currently quite limited. Hybrid methods employing high frequency techniques are currently employed to address these problems. However, these techniques leave large frequency bands with questionable results. I am referring mainly to the UHF, L-, and S-band regions where the HF techniques are not too accurate due to large wavelength compared to the size of the antennas and scatterers. Obviously these techniques fail in the VHF, HF bands…but there full solutions are possible unless the platform is very, very large."
>
> "The question of modeling structural interactions is difficult, because it is rarely possible to rigorously model both an antenna and its structure completely. In addition, the large number of structural geometries of practical interest, multiplied by the number of possible antenna geometries, leads to such a large variety of possible combinations that it seems to be impractical to expect packages to be able to accommodate such variety. Instead, I think it will be necessary to use a

> specialized analysis code for the antenna, and couple its output to a GTD, GO, or PO type analysis. One way to facilitate this approach would be to propose a standard form of output from antenna analysis packages for use with standardized GTD codes."
>
> "Antenna-to-Antenna Interaction on the Same Platform (Cosite Interference); very critical problem when multiple antennas are mounted on the same platform (which is usually the case in most cases)."

Along with these comes the warning,

> "If you are making a design tool, then (include mutual coupling effects) only if it affects the overall design. Otherwise put this capability into an analysis code. Mutual coupling can only dramatically increase run times."

This statement is only too true and that is why the toolbox should contain more than one code, and that each code should offer certain of its functions as options.

Another, frequently mentioned item, is the need for fast and efficient solvers. This is summed up in the statement,

> "Anything to speed up the analysis."

Some comments more specific than this,

> "All codes are currently too slow for large finite array analysis. The problems stem in system memory requirements and solver speeds. More effort needs to be dedicated to reduce problem size below NlogN to speed up the computation. NlogN is currently state of the art (FMM, AIMS, FSDS, etc. are all algorithms that help achieving NlogN.) Effort needs to be made to reduce it to O(N)."
>
> "Iterative and sparse matrix and other methods for getting numerical solutions for large problems represent an important area for advances needed in future codes."
>
> "Also hybrid methods using both time and frequency domain information simultaneously can generate results from DC to daylight on small platforms."

Speeding up an exact computational engine is not an easy problem, but it is not one we can walk away from. Without fast and accurate solvers, the future of ACEM as an analysis and design tool would be in serious doubt. As an alternative (but not a replacement), suggestions are made about generating tools that may not be very accurate but will bring us reasonably close to a desirable design,

> "Use the latest numerical algorithms for speed and accuracy:
> Not necessarily. I believe there is a need for conceptual design tools, which need to be really fast perhaps at the cost of accuracy. Perhaps some empiricism would help. In terms of a conceptual tool, I mean a code that would quickly let you know the best place on the structure to put the antenna and maybe a guess at size and weight. A conceptual tool with these capabilities could be integrated with conceptual tools from other disciplines (if you are building airplanes then these disciplines would most likely be structures and aerodynamics)."
>
> "Finally, the area where we need to concentrate more is in codes suited for antenna design. Until we get to speeds that produce true real time results, we must develop codes that have approximate to exact methods built in to allow design. The design engineer and the antenna design process cannot afford the hours required to input and wait for exact answers while in the early stages of design. The codes we currently have require a group of PhDs to run them and to interpret the results. We need approximations that indicate trends and major problems in terms of installation location, etc. Once a preliminary design is determined, one then needs the more accurate codes for design refinement. Currently numerical analysis and design takes too long and is too expensive."

Such tools are extremely desirable but not easy to come by. As the electromagnetic environment under consideration gets more complex, the possibilities for "quick and dirty" solutions quickly fade away. Nevertheless, it would be a worthwhile undertaking to collect known empirical and other formulas and convert them into usable code. A source of such information could be journals and periodicals, such as the Antenna Designer's Notebook of the *IEEE Antennas and Propagation Magazine* and the *Microwave Journal*. Another source might be all the companies that specialize in antenna design. It is highly unlikely, however, that they would be willing to reveal their proprietary design procedures. Another use for such tools is to provide quickly initial values for optimization algorithms.

A few of the participants told us about their computational engine preferences,

> "It is important to point out to the designers and users of antenna tools that for conducting structures – does not matter how complex it is – it is difficult to beat the efficiency and accuracy of an integral equation approach!"
>
> "Even with bulk dielectrics a surface integral equation in the frequency domain is more efficient than an FE based code."
>
> "Another emphasis should be the ability to solve all these problems with the efficient use of memory and CPU time. It is also imperative that many of the reflector

> antenna software be based on first principles of electromagnetic analysis such as the method of moments etc. This is only possible if fast solver technologies be used to develop these software.
> The MoM-SIE is recommended as a basic technique for solution of composite metallic and dielectric structures. It should be hybridized with:
> 1. High frequency techniques for electrically very large structures
> 2. MoM-VIE or FEM for anisotropic (bianisotropic) and/or highly inhomogeneous media."

We move on to specific items in the preliminary roadmap.

4.1 Additions, Enhancements to Part I.A of the TWGA Toolbox: Antenna Types

We did not explicitly mention certain types of antennas, and this was quickly pointed out by several people. A selection from the responses follows,

> "Cavity-Backed Dielectric/Ferrite-Loaded Antennas."
>
> "Plate-dielectric type of antennas (e.g., dielectric rod antenna, dielectric resonator antennas, dielectrically loaded horn antennas, etc.) (Another possible name for this class is composite metallic and dielectric antennas.)"
>
> "Antenna radomes."
>
> "Antennas for wireless communication."

Another item brought to our attention, and which is not explicitly mentioned in the TWGA toolbox, is a low RCS antenna structure,

> "Most non-commercial antenna designs now have RCS requirements associated with them. The scattering codes usually cannot handle antenna scattering. Low RCS apertures require aperture edge treatments, coatings, FSS radomes, etc., that is not modeled by existing codes. Antennas embedded in layered media are a challenge, especially if surface waves and other effects are to be included. A subset of this is a robust code capable of predicting performance of large arrays with low sidelobes or requirements for deep nulls. Such codes exist for pure metal plates with waveguide or cavity type radiators. However, there is nothing very good for embedded arrays."

Large but finite arrays, as well as, infinite periodic arrays were mentioned also by others.

Finally, one person provided a list of "building blocks" or "basic entities" that contribute to efficient antenna modeling,

> "Related with the list "I.A" and partly list "I.B", there is a question: Which are basic types of entities that can be used for efficient modeling of any above-mentioned type of the structure? One possible list is:
> 1. point generator
> 2. wires
> 3. plates (PEC patches)
> 4. dielectric patches
> 5. dielectric bricks
> 6. distributed loads
> 7. concentrated loads
> 8. infinite dielectric layers (and halfspaces)."

4.2 Additions, Enhancements to Parts I.B and I.C of the TWGA Toolbox: Code Attributes

Optimization appears to be a concern for some,

> "The inclusion of optimization near the top of the list is ambitious. Simply designing the code I/O so that it is reasonably easy for end users to develop their own interfaces, for example to visualize results on various slices through the parameter space, would be very valuable. That is, unless the supplied pre/post-processor is complete enough to do everything the user might want."

while its inclusion was lauded by others,

> "Yes, yes, a resounding yes. Of course I am in the optimization business, but this is exactly the type of thing you want to be doing as early as possible in the design process to reduce design effort and costs and increase performance."
>
> "In addition to design codes with varying degrees of approximation to exactness, we need to put more effort into optimization. Final optimization and tweaking can take anywhere from 30 to 50% of the design time. Optimizers are needed (1. impedance (VSWR) & bandwidth, 2. Pattern & sidelobe optimization, 3. RCS reduction)."

Indeed, generation of optimization software for antennas is not a simple task. Other engineering disciplines, however, have made good progress in this front. Maybe we can learn from their experiences. Design optimization should not be a mathematical problem that leads us to *the* global optimum of some quantity of interest; rather, it should be a philosophy of design that combines mathematical optimization with other processes to arrive at a satisfactory set of design parameters. One suggestion along these lines is,

> "Parametric sweep as a function of various geometry and material parameters is fundamental to the design process and oftentimes helps narrow down the range of parameters for optimization. Sensitivity analysis is also important from a manufacturing point of view."

Some participants caution us that good computation of near field quantities requires careful modeling of the region around the antenna feed,

> "Two areas should be emphasized, the ability to model disparate length-scale, i.e., a combination of fine geometry details requiring very fine meshes together with smooth surfaces where coarser meshes can be tolerated. This would eventually give rise to better antenna software for the input impedance of the antenna."
>
> "Most antenna codes usually do well in predicting radiation pattern behavior. However, the majority of antenna codes are also deficient in predicting the input impedance well. One can get an idea of impedance behavior with voltage or current sources, but it is not usually what is measured at the connector. More effort has to be placed in realistically modeling the feed (including the connector). This will have to include the ability to do adaptive meshing in cases with fine structure."

We add to this that, quantities directly related to near fields (e.g., input impedance), require not only better adherence to the original geometry but, also, higher precision computational levels than far-field quantities. This is because the latter are obtained through an integration of near-field quantities (currents) that smoothes out much of the error present in them. Thus, the accuracy of an antenna code that claims to compute near-field quantities should not be judged by its far-field results but by those in the near field.

Geometry generation (modeling) is to ACEM what ACEM is to modern antenna design. We simply cannot do without it. It looms large in the community and is rather controversial. Some believe that geometry generation should be provided by the major CAD houses,

> "Meshing (producing geometry) is probably the biggest handicap in utilizing codes. I believe that the CEM community and aerospace industry needs to make it appealing for the major CAD packages to include surface and volumetric meshing

> suitable for CEM in their packages. The CEM community should not be trying to reinvent the wheel by creating our own CAD meshing packages for EM modeling. A coherent strategy needs to be developed with commonality between the packages."

Certainly, reinventing the wheel is not a good idea. Another reader reminds us, however, that,

> "CAD models are widely available, but almost always have to be pre-processed before they can be used by computational codes. This is a currently a major issue in applying FMM-type solvers (as well as other codes). One also needs to remember that different computational codes have different geometry requirements and the philosophy "one-size-fits-all" is not likely to work here."

It is true that every computational engine has its own geometry representation requirements. For this reason, one user advocates that,

> "Efforts should be focused on usability, e.g., ridding every EM code from its dependence on external geometry generators, inclusion of optimizers, etc. These enhancements will remain even after a thousandfold increase in computer speed and memory."

The right choice probably lies somewhere between the two extreme positions and is driven by market forces. It would be nice for a major CAD house to develop capability that caters to the major CEM/ACEM computational engines. Is it, however, a profitable proposition at this time? On the other hand, should we expect every ACEM code to be geometrically self-sufficient? That is asking a lot. One way of achieving this would be for a low-overhead company to produce a geometry pre-processor that would convert CAD geometry to one understood by a specific ACEM code. The "understanding" should not simply involve just a simple step, like "convert to triangles", but a conversion to a geometry optimized for the given computational engine. This would require a collaborative effort between the ACEM code developers and the geometry house.

When we speak of geometry generation, it is usually the large airframes, ships, etc. we have in mind. Some ACEM codes do have the capability of generating geometry for simpler structures, especially antennas. We should then also develop ways to join an antenna generated by the ACEM code to an airframe that is imported into the code. There were no comments on this issue.

Some suggest that we specify geometry file exchange formats,

> "As far as accepting different file formats is concerned, some formats should be specified, such as DXF, IGES, etc. Also, maybe some examples of software capable of model (mesh) generation, such as I-DEAS, PATRAN, NASTRAN, etc."

> "It would be useful to set a standard input format for 2D and 3D mesh geometries for a number of the government owned codes, including a set of basic feeding methods (delta-sources, coaxial, waveguide, aperture coupled, etc). Comparisons of several analysis approaches would be much easier as a result. Commercially available drawing packages such as PATRAN or I-DEAS could be used as a framework for the input formats."

Deciding on geometry file formats should be part of the design of the geometry pre-processor. As for the commercial CAD packages mentioned, none is designed for CEM applications. Their output, however, can be "massaged" by a well-designed pre-processor to make it palatable to a specific computational engine.

We conclude the remarks about geometry generation with a little tale that points out that, when modeling complex antenna structures, we not only must reproduce geometry faithfully but also properties of materials,

> "There is also a need to improve the models, especially using FEM, for cavity type antennas with materials inside the cavities. Several of our codes have had discrepancies between the computed and measured resonant frequencies. The percentage difference can be as off as 5%. We have attributed this to assuming PEC for the walls of the cavities. When we include a skin depth (material/metal losses), the resonant frequencies begin to agree with experiment."

The subject of standardization comes up again in talking about I/O capabilities,

> "With standardized inputs, it may be possible to develop an optimization shell, whereby a design optimization code is 'wrapped' around an antenna analysis engine. The optimization shell could be general enough to utilize a variety of computing codes, (seeking to optimize the defined output parameters as a function of defined input parameters). Preferably the government-owned codes referred to above would be used as the engines, and the I/O formats would be standardized."

The point is well taken; however, we are not quite certain it is within the purview of this committee to establish standards for ACEM software. We feel that this is more the responsibility of an appropriate IEEE committee. Every IEEE Society has in its Administrative Committee a member responsible for Standards. One suggestion we can make is for the EMCC to approach the Antennas and Propagation Society of the IEEE about forming an exploratory committee on this issue.

Staying with this statement, we contrast it to a statement made earlier on,

> "Efforts should be focused on usability, e.g., ridding every EM code from its dependence on external geometry generators, inclusion of optimizers, etc. These enhancements will remain even after a thousandfold increase in computer speed and memory."

This case advocates code self-sufficiency, i.e., all components of the code (mesher, optimizer, computational engine, post-processor, etc.) being a well-integrated part of the total package. The previous case opts for the components being independent modules that can communicate well with one another. We may argue that the integrated package will be more efficient while the modular package will be more flexible and easier to upgrade. All these issues should be debated before making recommendations.

There is some concern that these codes may be designed for large computer platforms only,

> ""Scalability" of the software would be very useful. That is, most or all features can be used on a reasonably good workstation. Using a faster computer with more memory improves execution time and increases the size of the problem that can be solved. But, it is desirable that everyone not be required to purchase the latest, greatest computer just to benefit from the tools."

This is a legitimate concern since a lot of antenna analysis and design can be done using a "reasonably good workstation"; indeed, quite a few of today's antenna software are written for popular computting environments, such as Windows XX or NT. For large applications, however, we may have no alternative but to resort to large machines. In this respect, DoD contractors may find the DoD HPC Centers an invaluable resource for their computing needs (see http://www.hpcmo.hpc.mil/). Use of these facilities presupposes that codes are written so that they can run on the scalable architectures found there. Mr. Ron Chase (rchase@arl.army.mil), current Chair of the EMCC, presents his view on this matter in Appendix G.

We did not expect a dissenting view on the matter of a GUI but we got one,

> "With respect to GUI, I would leave it out in the initial list. A GUI implies a commercial product and should not be considered under the same roof with the development tools."

Research and development efforts do play a prominent part in the roadmap. The ultimate objective, however, is a collection of software tools that will make antenna and antenna/platform analysis and design possible. The end users are the final arbiters on this and their messages are clear and unambiguous,

> “I believe that the Road Map does an excellent job in presenting what is really critical to antenna modeling and analysis engineers and scientists. However, the GUI interfaces should be stressed further that they have been. Ease of use should be an important goal as well.”

Past experience shows that, once ACEM engines have been developed, it is very hard to find government sponsors who will pay for the “peripherals”, such as a good GUI. For this reason, it is a good idea to make such items part of an ACEM project from the outset.

The capability to account for the presence of a helicopter rotor (and the resulting signal modulation) was also mentioned as a desirable code attribute. Indeed, a rotating wing or propeller, or anything else in motion, is computationally expensive. Currently, the effect of a rotor is computed in a static sense, i.e., the position of the rotor is fixed and the code is run. This has to be repeated for very many positions at great cost. This is a basic research area in which very little has been done and is worth funding.

A few other suggested code attributes are,

> “I would include
> Matrix Boundary Conditions
> Higher order boundary conditions
> Higher order elements.”

4.3 Additions, Enhancements to Parts I.D of the TWGA Toolbox: Types of Codes

We will not dwell long on this topic for it is generally acknowledged that every exact computational method is useful for some class of antenna problems,

> “The list of desired code capabilities seems fairly complete. While one can conceive of a code which does everything on the list, it is not likely to be the most efficient approach for all antennas. There will always be a trade-off between generality and efficiency.”
>
> “I believe antenna CAD is best implemented by a *suite* of packages that are tailored to specific antenna geometries. For example, wire antennas are best treated with moment method techniques, in terms of entering problem geometry, computational efficiency, and interpretation of results. A finite element program (e.g., HFSS) can also handle wire antennas, but it is difficult to specify the input geometry with HFSS, and it is much slower in terms of CPU time. Similarly, microstrip antennas are best treated by moment method solutions using Green’s functions for dielectric layers, and are not handled very well with finite difference or

finite element methods. On the other hand, finite difference and finite element packages can treat very general problem geometries, especially when inhomogeneities are present."

Moreover, having more than one computational engine available does help,

"Having dual or multiple engines for analyzing or designing a certain antenna gives the designer the flexibility over accuracy, speed, memory usage and the problem size limit. Specifically, the combination of a full-wave engine and an approximate analysis technique (e.g., based on network models, array factor, etc.) is highly desirable."

This last comment in this quotation ties well with earlier comments about "quick and dirty" design approaches.

4.4 Additions, Enhancements to Part II of the TWGA Toolbox: Antenna-Platform and Antenna-to-Antenna Interaction Tools

There is general agreement that the way to go when considering the antenna/platform combination is by using hybrid codes,

"Section II of the document on Antenna Platform and Antenna-to-Antenna Interactions is particularly well drafted. The development of this type of EM codes should be seriously encouraged."

In Part II.B, we were corrected on our assumption that FEM is the only effective method for dealing with antennas in cavities,

"As evidenced by paragraph II.B, there seems to be a general perception that the FE method is the best or only way to analyze complex cavity antennas. This may be due to the fact that early MoM codes failed in cases where tiny facets are required to capture geometrical detail. More recent MoM implementations do not fail in such cases and, in my experience, are not only easier to use, but also more efficient than FEM codes. This is because the size of the elements is driven by the smallest geometrical detail causing the number of unknowns to explode if there is an appreciable volume to grid. Of course, a volume formulation of some kind will still be required for anisotropic material."

Part II.D produced a rather strong reaction from two participants,

> "I agree that an end-product HF code devoid of any hybridization would be unduly restricted in applicability. On the other hand, HF algorithm development should certainly be pursued, and not all HF algorithm development will be directly related to the issue of hybridization. To ensure that this distinction is not overlooked, I would recommend changing D to read:
> D. HF algorithm development should be encouraged with the understanding that all end-product codes must be able to account for complex antenna structures, presumably via some hybrid scheme."
>
> "While the HF methods for calculating scattering have been around for some time, only recently, new methods significantly expanding their capabilities and precision have been discovered (AAPG, DOVA, CDOVA, Xpatch, though the latter one is an RCS code). This suggests that excluding development of HF interaction codes is a wrong thing to do. (Fast Multipole Method (FMM) could have been a victim of such "exclusion" less than 10 years ago!) The statement in part D of SECTION II is not proposing a strict exclusion policy, but it is quite strong. For example, I think that developments leading to utilization of CAD models of platforms by HF-based (and other CEM) codes are critical and should be encouraged."

and an opposing view by another pair,

> "Asymptotic techniques have been beaten to death in the last 30 years. This is not to say that there isn't anything new in this arena. However, we need to concentrate in fast numerical solvers and algorithms."
>
> "I tend to favor exact methods for on aircraft antenna patterns, since there is little reason to question the results. (High-frequency) Codes like (name removed) are used improperly more than not, and cannot deal with radiating structures in the near field of a platform, which is the norm and not the exception. The mind-boggling increase of computer speed and power will likely continue, exceeding even Moore's Law. As this pattern unfolds, high frequency methods will become correspondingly less desirable."

Perhaps, in the first line of Part II.D we should have placed the word *antenna* in front of the word *interaction*. We are by no means advocating stopping further research and development of high-frequency codes. As long as there are electrically large structures, there will be the need for good high-frequency codes. In Parts II.A and II.B, we strongly advocate the use of such codes in hybrid schemes. We have doubts, however, that such codes can predict the near-field behavior of a complex antenna structure, even when it stands alone in space.

4.5 General Remarks

We conclude this section with some material that does not fall in any of the above categories. If there were to be a prize for the best quotation, it should probably go to,

> “The "map" seems mostly complete and valuable. However, the devil is in the details.”

How true, and which makes this kind of a survey so much more necessary!

Some participants offered very good ideas and others raised legitimate concerns. One of the ideas has to do with lessons learned,

> “I would tend to agree with everything that is contained within that document. In addition though, I think that some sort of "best practices" list should be developed. For antenna designers who use computational EM tools, it would be good to have a resource which would be a collection of lessons learned by others in using different tools and methods.”

We will return to this topic in Section 10.

Concerns raised are

> “One issue not addressed in this document is user support and support for continued code development. How will this be guaranteed? Should the codes be developed in such a way that outside groups can add to them in the future?”
>
> “Another issue is code availability. Will such codes be available as public domain codes, or available only to users working on government contracts? Will they be made available to researchers in the universities? Will source code be made available?”
>
> “The list of capabilities requested is almost complete. However, in our experience with antenna design we have encountered issues with the software only solvable by having the source code available for modification… Supplying the source code for the antenna-platform calculation engine as well as the GUI software is the most efficient way of realizing antenna designs, although proprietary agreements may then be necessary.”

These are legitimate concerns that the TWGA can relate to the various Government agencies and make recommendations. The matter of user support can be resolved in a variety of ways, including the above-mentioned database of lessons learned. Another possibility is a Web based network of users, were one can ask for help from fellow users. Whether source code could become available, code made available to universities, etc., are issues that have been addressed in the past for similar codes, and we do not expect the policies to change any time soon.

We conclude this rather long section with two admonitions,

> "A very comprehensive WISH list!"
>
> "It seems unnecessary to 'reinvent' capabilities that already exist, especially if thousands of man-hours have been invested (either privately or federally).

To the first, we reply that, indeed, what we have put together is a wish. A list that might help DoD and other federal agencies invest their dollars in the right projects. To the second, we say that some capability is out there and some is awaiting development. We want to make sure that when everything is said and done, the antenna designer has a toolbox with user friendly tools that do not require an army of Ph.D.'s to make them perform.

Section 5. Part III of the Survey: Participants' Involvement with ACEM Software

In Part III of the survey, we asked the participants to list and critique ACEM software they have developed or have been using. We also asked them to suggest enhancements along the lines of Part II of the survey.

The responses can be found in raw form in Appendix C. A number of codes are mentioned there, some well-known and some recent ones. We grouped these codes according to their computational engine. We thus have the following five groups: FDTD, FEM, MoM, high-frequency method, and hybrid codes. In the first four groups, each code has only one computational engine, while in the fifth there are at least two. The computational engines of the first three groups do not approximate the physics of the problem and, hence, are known as exact methods. High-frequency methods do approximate the physics and are, thus, approximate methods. Hybrid codes can be either.

We begin with the exact-method codes, in alphabetical order, and then move on to the high-frequency and hybrid codes. Here are the inputs for the first group,

FDTD CODES

"**NEWS** (Numerical Electromagnetic Wave Simulator). This is an FD-TD based code that we have developed to analyze radiation, scattering and penetration problems, especially for complex platforms (i.e., helicopters, airplanes, ground vehicles, etc.). The code is interfaced with other available software (especially **BRL-CAD** based) to automate the geometry (**MGED**), meshing (**ANASTASIA**) and **IMAGE** (geometry viewer) of the system. Various different post-processing software (**GLE, DRAW**, **TECPLOT, PLOTMTV**, etc.) are used to process and illustrate the data."

"We are using FD-TD codes both home grown and commercial (**XFDTD**)."

"NRL Multi-layer **FDTD3D**: 3D FDTD total field formulation with YEE-like material absorbing boundary conditions and lossy multi-layer media."

"REMCOM **XFDTD**: 3D FDTD code. NRL has modified the 1995 source code to handle multiple feeds, 128 materials, and to generate admittance matrix data for antenna array mutual coupling for post-processing active array scan VSWR. The more recent versions of **XFDTD** probably have greatly expanded capabilities."

"NRL **FDTDGEOM**: Grid generation software for NRL FDTD3D and XFDTD. Outputs geometry files to be viewed in AVS and MCAD as well."

In the fourth item above, we see the need to modify (commercial) source code to suit the user's needs. This subject of source code availability was also brought up in the previous section. We believe that such arrangements can best come about through negotiations between user and developer.

The list of FEM-based codes includes the following ones,

FEM CODES

"We are in the process of developing another software package, similar to **NEWS** (see FDTD group) but based on FEM. It also is intended to address radiation, scattering and penetration problems, especially related to complex platforms."

"**PARANA** (home grown)

a. 3D finite element frequency domain
b. Infinite array periodic boundary conditions
c. Multiple ports
d. Accepts PATRAN and IDEAS geometry files
1. No GUI."

"**XP3**

a. 3D finite element frequency domain
b. Infinite array periodic boundary conditions
c. Multiple ports
d. Accepts PATRAN and IDEAS geometry formats."

"We utilize **HFSS**."

"**FSS-PRISM** and **FSDA-PRISM**: Extremely fast O(N) CPU and memory codes for Frequency selective surface and array modeling on infinite and finite substrates."

and we have no comments on it.

By far, the largest group of codes is the one based on the MoM,

MoM CODES

"We are using, especially for validation, the **NEC** code. We found this to be very good for most cases."

"We utilize **NEC**."

"**NEC** – Excellent MoM code for wire antennas. Patch capability is very limited and non-effective. Really like its allowance for symmetric and non-symmetric portions in a single model, as well as its rotational symmetry. Runs in both single and double precision modes. Needs a really good GUI (even better than what comes with **GNEC**).”

“One antenna software we have developed in our Center is **FISCRAD**, and Fast Illinois Solver Code for Radiation calculation. It can handle wires radiating in the presence of complex platforms such as an aircraft or ground vehicle. However, we do not have enough resource to push for a more matured development of this software. Our Center has to develop scattering codes, material scattering codes, as well as this code.”

“**ANSOFT-Ensemble**: Method of Moment solution to analyze and design multi-layer microstrip antenna problems.”

“We utilize **Ensemble**.”

“**Ensemble** – well known commercial MoM code.”

“We have developed **WIPLD** which is a commercially available software capable of solving real life problems in reasonable time on a PC. It can handle most of the problems cited in the document. However for FSS a Floquet type expansion can be more advantageous. However for a finite sized composite structure **WIPLD** is the only commercially available code at a reasonable price available to any interested researchers with modest means.”

“**WIPL-D** – Excellent MoM code for both wire and plate antennas and structures. Very good code with good pre- and post-processing interfaces. Needs a double precision version. Allows for multiple material definitions. Variables can be defined using symbols, thus simplifying changing the values of like variables. **WIPL-D** allows for PEC, PMC, symmetry, and anti-symmetry options, among others. Double precision mode is not currently available. Some aspects of the code need improvement. Currently, if a source lies in a region of symmetry, the source is automatically transferred with that region. This is not a desirable situation, since source magnitude and phase values could vary considerably from one source to another. However, that same scenario is not true for a load in a region of symmetry, which normally is desired to be transferred with the region of symmetry. Also, there are options in the Windows version of the code that are currently not fully operational.”

“I use **NEC** and **WIPLD** exclusively. The one reason to use **NEC** is its ability to exploit rotational symmetry—body of revolution that permits asymmetrical excitations—very powerful indeed.”

“"Homegrown" MoM codes for analysis of infinite arrays of wideband Vivaldi tapered slot antennas. Used on medium level workstations. Lack good user interface and thorough documentation. Only useful for the canonical geometries for which Green's functions have been implemented. There is need for better codes to treat infinite and finite arrays of complicated elements (dielectrics, printed and machined metal parts, lossy and/or anisotropic materials)."

"**TRIMOM**: moment method code using the Rao-Wilton basis for antenna and scattering."

"**TRIMOM-FMM**: moment method code with fast multipole method."
"In our group we also are end users of the code **IE3D** by Zeeland software. This is a very versatile MoM code for analyzing either antennas in free space or in a layered media. This software tool has a very good GUI, which is one of its strong points. We use ACEM codes to design microstrip antennas, and antenna for wireless communications."

"Multi-layer infinite array printed microstrip/dipole analysis code (developed at AFRL)
    Electric field integral equation – frequency domain
    Probe feed and proximity coupled line feed
    Dual and circularly polarized feed analysis
    MoM with entire domain and sub-domain PWS basis functions
    Conjugate gradient solver
    No GUI"

"**ESP4**: OSU MOM 3D software with plates and wires."

"**PiCASSO** is an antenna design software developed by EMAG Technologies, Inc. under a SBIR program funded by Army during 1996-99. It is meant for the analysis, design and optimization of printed antennas and arrays. Its main engine is based on the method of moments using a mixed potential integral equation formulation. It can handle an unlimited number of substrate layers and trace planes or ground planes. It is also equipped with a sparse moment method solver that enables the user to solve large-scale problems with more than 20,000 unknowns.
In addition to the full-wave engine, **PiCASSO** also has a model-based network engine. It can generate network models from full-wave simulation data and use them in a multi-port network analysis. The coupling effects among the array elements are taken into account through full-wave-based coupling models. **PiCASSO** also offers pattern synthesis capability through its genetic algorithm optimization engine.
Many of the features suggested in Part II (of the survey) have already been implemented in **PiCASSO**, e.g. multi-variable parametric sweep, dual full-wave/network engine, etc. Under DARPA's RECAP program, the **PiCASSO** foundation is currently being enhanced with new features including a finite element engine for handling of MEMS structures and a periodic moment method engine for frequency selective surfaces and photonic bandgap structures. Under CHSSI program, a parallel version of **PiCASSO** and parallel versions of the subsequent finite element and periodic engines will be developed.
In the future, additional simulation engines including a time domain simulator will be added to **PiCASSO**."

"Finite Element Radiation Model (**FERM**) (developed at MIT Lincoln Lab)

1. Electric field integral equation – frequency domain
2. Plate type MoM
3. Delta gap sources
4. Infinite and finite ground planes
5. No dielectrics
6. No GUI."

Not only is this the largest of groups but, also, there is considerably more discussion of the various codes on the part of both developers and users. This is something we encouraged in the survey but we did not get for all codes mentioned.

This concludes the presentation of codes that use an exact computational engine. The next group is codes that use a high-frequency approximation method,

HIGH-FREQUENCY CODES

"Reflector code from University of Illinois, Champaign, IL: Developed by Professor S. W. Lee using PO/UTD to analyze and design various reflector antenna configurations."

"I have been heavily involved with the development of codes known as the Aircraft inter-Antenna Propagation with Graphics code (**AAPG 2000**), and Diffraction Over Virtual Aircraft (**DOVA**). These codes employ the Uniform Geometrical Theory of Diffraction (UTD) in conjunction with novel ray trace techniques to compute patterns and coupling effects for platform-mounted antennas. Unlike previous UTD codes based on canonical shapes, these codes employ a realistic platform representation in terms of triangular facets. The ray tracing involves selection of starting paths, followed by convergence to extremal paths via a "diffusion" algorithm. The implementation of the UTD within these codes includes both wedge and smooth-surface diffractive mechanisms. Inclusion of the latter is possible because the facet representation has been demonstrated to reliably support UTD treatments for smooth surfaces.

The **AAPG 2000** code is used extensively at the DoD Joint Spectrum Center to assess the electromagnetic compatibility (EMC) of aircraft-mounted electronic systems. The **DOVA** code has not yet been completed.

Suggested Enhancements:

—Hybridization of both of these codes is under investigation. This is an essential step, as noted earlier.

—Platform material properties need to be included in these codes. An important but difficult problem derives from the fact that these codes should be able to predict shadow-region patterns and coupling in cases involving the creeping-ray mechanism. Even for a conducting surface coated with a single layer, or a simple impedance surface, no creeping-wave solution has been available for cases where

the surface has general curvature in two directions. I proposed a solution at the APS/URSI meeting last summer, and am currently working towards implementation into **AAPG 2000**.
—Our ray-trace scheme is oriented towards aircraft. This algorithm places no limits on the number of times a diffractive mechanism is allowed to occur, but each path involves at most one reflection. The inclusion of further reflections would help to make these codes more applicable to a shipboard environment."

"Matis, Inc. has developed:
—Propagation Path Finder (**PPF**) – the geometry engine of **AAPG2000**, currently in use at Joint Spectrum Center (via IITRI) for EMI/EMC predictions.
—Diffraction Over Virtual Airframe (**DOVA**) – a code for predicting the "net" patterns of airborne antennas. The code is designed to perform required calculations on platforms modeled by realistic CAD-based models. It has an extensive user-friendly GUI and a post-processing utility for viewing and printing the results. It also includes visualization tools for viewing in real-time the platform, propagation paths, etc.
—CDOVA – a code for predicting coupling/isolation between pairs of airborne antennas. It also runs on realistic CAD-based models, has a GUI, a visualization, and a post-processing subsystems.
Both, **DOVA** and **CDOVA**, are HF codes. Both run in nearly real-time on a low-end workstation. They are real-time when run on a multi-processor machine or a network of computers. Currently, both codes accept six classes of basic antennas modeled with pattern factors. More information about **DOVA** can be found at www.matis.net.
One important enhancement would be to link the **DOVA** and **CDOVA** with an exact code(s) with capabilities to model large antennas. Provisions for such enhancements are built into **DOVA** and **CDOVA**.
Another important enhancement is to add capabilities for running **DOVA** and **CDOVA** on CAD models representing platform surfaces by NURBS (Non-Uniform Rational B-splines). The currently used CAD models must be faceted. For several reasons simple format conversion from NURBS representation to faceted, while possible, is not always desirable nor is the most efficient way to approach this problem."

"**NEWAIR** – Based on GTD/UTD. Antennas handled are limited to monopoles and slots attached to aircraft fuselage. Does not compute mutual coupling between antennas, antenna parameters, or currents on antennas or mounting structure. Does not handle wires, and does not have a graphical display for Windows environment."

"**NECBSC** – Based on GTD/UTD. Still in a beta-mode, and is being updated continuously. Antennas handled are limited to dipoles, monopoles (limited success), circular and rectangular loops, and slots. Doesn't compute mutual coupling between antennas, antenna parameters, or currents on antennas or mounting structure. Wire modeling has just been added. Has a graphical display/interface for

Windows environment, which is being continuously updated."

An article describing the capabilities of **AAPG 2000**, a relatively new code, appeared in the *IEEE Antennas and Propagation Magazine*, Vol. 42, No. 2, April 2000, pp. 100-106.

In the next group, we find codes that have more than one computational engine. Without exception, the two computational methods are the MoM and the FEM. The MoM is used on boundary integral equations on the surface of the object, while the FEM in cavities that are filled with materials and may contain antennas. Some well-known codes are included in this group,

HYBRID CODES

"We have developed an in-house computational EM code named **CARLOS** which is described in the April 1993 AP Magazine on page 69. This code was developed primarily as a RCS analysis tool, but is also applied extensively within Boeing for antenna modeling. It is a surface integral equation method-of-moments based code using triangular or quadrilateral patches for 3D geometries, although it can also model body-of-revolution (BOR), wire, and 2D geometries. The code has also been coupled with a finite element code (**CAFE**) forming a hybrid MM/FEM capability for modeling interior inhomogeneous or anisotropic materials. The code has been successfully used to model a variety of antennas, including spiral, patch, flared notch, Vivaldi, monopole, and slot type."

"**CARLOS**: MoM-FEM 3D software."

"I am a developer and user of the **CARLOS** code and its hybrid versions using FEM and asymptotic techniques. These codes already satisfy many of requirements outlined, but there is still much work to be done. Specifically, a "fast" solution approach is needed for large problems (i.e., platform integrated antennas) and new basis functions (namely, loop-star) are needed for low-frequency problems. The code is also rather difficult for the nonexpert to use and since it is not distributed commercially, user friendliness has always been a low priority."

"At Applied EM Inc. we are developing **ASET** – Antenna and Scattering Evaluation Tools, state-of-the-art antenna analysis code. By the use of multi-resolution elements and smart matrix solution algorithms, the memory and CPU times requirements are reduced. Platform interactions with the antenna are included in the analysis to characterize the antenna at multiple locations on the platform. Decoupling of antenna analysis and platform analysis is achieved through accurate and rigorous analysis. Despite of the large gains in terms of memory and CPU time, the real life platforms are electrically very large in size and require parallel computers to solve the problem in reasonable time. Fast techniques such as FMM and AIM will make this software a viable tool that can be used on a desktop PC for the analysis and optimization of the antennas on large platforms. **ASET** software is based on MoM with multiresolutional elements and fast algorithms. Cavity-backed antennas are analyzed using FEM/MoM based technique. **ASET** software is being successfully used to characterize antennas on aircraft, automobiles and ships."

"**BRICK/XBRICK**: finite element-boundary integral code for conformal antenna analysis using bricks for modeling the volume and squares for the surface."

"**FEMA-PRISM**: similar FEM-BI code to **BRICK**. It uses prisms for the volume and triangles for the surface."

"**MR_TETRA**: FEM-BI code for antennas. Use tetras for volume and triangles for surface. Also it incorporates multiresolution elements which are crucial for input impedance calculations."

"**ARRAY_TETRA** code for antennas. Similar to **MR_TETRA** except for periodic volumes and surfaces. Both, **MR_TETRA** and **ARRAY_TETRA** incorporate fast algorithms."

"**SWITCH-FMM**: general purpose scattering and antenna analysis code based on Northrop's **SWITCH** code. It includes fast multipole method and FEM. Was developed with Northrop-Grumman."

"The **EIGER** software suite is a general-purpose hybrid FEM/MoM framework. The tools use both higher order geometry and basis functions. The MoM features can incorporate Green's function treatments for multi-layered materials and periodic structures (as well as combinations of the two). The tools also allow a variety of boundary conditions ranging from PEC and PMC to general materials, apertures and impedance loaded surfaces. General symmetries are also available for reflection and discrete rotational geometries. Different combinations of these features can be applied simultaneously to different portions of a complex problem. The list of antennas recently designed with this tool suite include (but aren't limited to) the following:
—Broad-band wire radiators
—Microstrip patches
—Spirals (equiangular, archimedian, and sinuous type) both planar and non-planar
—Broad-band horns
—Reduced surface wave antennas
—A variety of phased array and FSS geometries
Additional information can be found at the following Web address beginning May 12, 2000: www-cce.llnl.gov."

"I have assisted in the development of post-processing tools for **EIGER**, an multi-purpose object-oriented computational software tool being developed jointly by Lawrence Livermore National Laboratories, Sandia Laboratories, and the University of Houston. I believe that **EIGER** is a leading-edge ACEM tool that shows the future for software development in this area One of its main characteristics is that it is based on object-oriented FORTRAN 90. This object-oriented approach allows different types of basis functions to be modeled in a unified fashion. In this approach the incorporation of different types of Green's functions into the code to treat different types of canonical problems becomes much more direct, avoiding the necessity of writing entirely new codes to treat different geometries. New types of basis functions can also be directly added to the code without re-writing the entire code. This is because the object-oriented approach allows for a unified treatment of reactions between basis functions using various Green's functions. For example, modeling the reactions between basis functions in diverse problems, such as triangular roof-top functions on a flat plate of tetrahedral elements inside a volume, is thus done using the same code. If new basis functions are added in the future, a new type of basis function class is simply added. The object-oriented approach also allows for post-processing parts to be added to the code with minimum effort. This allows for the calculation of figures of merit such as antenna gain, efficiency, etc., to be added to the code in a direct way. This code therefore provides maximum versatility and expandability, which is one of the most important requirements for multi-platform ACEM software."

No hybrid codes that have a high-frequency computational engine as one of their engines have made their appearance yet.

Finally, there are some codes whose engines were not specified,

CODES WITH UNSPECIFIED ENGINES

" "Homegrown" codes are used to design and analyze reflector-based antennas."

" "Homegrown" codes are used in planar array designs."

"NRL is using several packages in addition to ones we have developed to design Ultra-Wide-Band phased array antennas for a number of applications."

"I have developed **PCAAD 4.0**, the fourth version of a Windows-based package for general antenna analysis and design (wires, arrays, microstrip antennas, horns, reflectors, etc). This package uses simple cavity-type models and aperture integrations, and is relatively inexpensive. I have also developed about a dozen specialized codes for the full-wave analysis of microstrip antennas and phased arrays. I occasionally use **Ensemble** (see FEM group above), and my students occasionally use **Momentum**."

"**PCAAD** - this is a relatively simple analysis tool developed by David Pozar, Antenna Design Associates. It is easy to use on a PC and provides good starting point information for antenna design or for more extensive analysis. However, it is limited to the particular cases that it was designed to analyze."

> “**CADRISA**: General purpose scattering and antenna analysis code using the Adaptive Integral Method (AIM). Code can handle various material and impedance regions/surfaces as well as general junction. This is a very new code.”

This concludes the listing of codes that appeared in the survey.

Section 6. Part IV of the Survey: Near-Term Principal Thrust of ACEM Research

In Part IV of the survey, we asked the participants to tell us what the principal thrust of ACEM research should be in the next three to five years.

The responses can be found in raw form in Appendix D. Many issues are brought up but the one that dominates is hybridization.

The comments on hybridization arise mostly out a concern of how to handle complex antenna systems on electrically large structures. This is a situation that requires high-precision exact codes (if we are to compute antenna near-field quantities) over very many square-wavelengths of platform area. This is not possible today, or in the near future; hence, the need for hybrid codes. The high-precision exact code will be exercised over the antenna region, while a high-frequency code will be used on the rest of the platform. What constitutes the antenna region, how the two codes will be coupled, and whether some quantities will be iterated between the two codes should be part of a research and development effort. These thoughts are echoed also in some participants' comments,

> "I also very strongly believe that Hybrid Methods will be the ones that will solve electrically large structures, the same way as it was stated in the road map. That is, treat the antenna and its vicinity with a low frequency method (such as FEM, FDTD, MoM, etc.) and the remaining large part of the structure using a high-frequency method (such as PO, PTD, GTD, etc.). Otherwise it will be a long time before larger structures are treated accurately just with the limitations of each one of the individuals methods has."
>
> "Develop hybrid antenna codes capable of running on CAD models, faceted and NURBS. Issues related to accuracy should be also investigated. This is very much in agreement with the discussion in part B, section II."
>
> "Hybrid codes and fast methods for treatment of structures combining large and small parts."
>
> "It is difficult to give the same advice to different research groups. Actually, everybody must improve his own method, but with the same goals: to increase the flexibility, accuracy, and efficiency. The general trend is hybridization. However, it is not so easy. For example, the MoM specialists are far away to be specialists for high frequency technique, and vice versa. One possible solution is to join these specialists. Another possibility is to make independent programs (e.g. one MoM, and another high frequency) that are able to communicate. If the language of communication is standardized, different hybridization can be made. (For example, the hybridization is always performed through boundary surfaces. In my opinion optimal elements for description of boundary surfaces are RWG triangles and WIPL quads. They can be used as standard elements for communication.)."

> "I would say the development of tools for predicting the antenna/platform interaction effects based upon some sort of hybrid approach."
>
> "Full hybridization."
>
> "Hybrid methods development."
>
> "Antenna-platform and antenna-to-antenna interaction tools are needed."
>
> "Isolation between apertures."
>
> "Installed antenna performance is inherently a multi-scale problem. Research should be directed toward numerical methods tailored to this class of problems."

These statements re-iterate the concerns expressed above and in Part II of the TWGA Toolbox (see Section 2). We need codes to analyze/design complex antennas on electrically large platforms and hybridization between one or more exact method and a high-frequency method seems to be the way to accomplish it.

Besides the need for the mating of exact and high-frequency codes, we saw in the previous section that we can have hybrids of exact codes. Additionally, one participant points out the necessity for another type of hybrid code,

> "As more sophisticated antenna systems gain practical applications, there will be a need for more complex antenna design tools. One example is reconfigurable aperture antenna arrays, which span different technologies and pose various modeling needs. The principal thrust of ACEM research for the next three to five years should be hybrid modeling tools that combine different techniques to treat complex antenna structures. Such techniques are needed for both antenna design and study of antenna-platform and antenna-to-antenna interactions. Hybrid moment method/network, FEM/network and MoM/FEM codes will be useful for analysis and design of antenna elements and arrays, while hybrid MoM/HF and FEM/HF codes will address the study of antenna interactions."

If we understand this correctly, in addition to considering the antenna and its platform, we must also provide appropriate software for the antenna's feed network. This is another item that was not mentioned explicitly in the preliminary antenna design toolbox and which is as important as the rest. In principle, exact codes should be able to handle feeds. If, however, they are designed for the purpose, then they should be more efficient than a general-purpose exact code.

Following closely behind hybridization is the area of fast and efficient methods,

> "ACEM research should be focused on development of fast algorithms for antenna analysis. These include but not limited to FMM and AIM techniques. Fre-

quency extrapolation techniques such as AWE and MBPE are essential to be incorporated into the ACEM codes to characterize the antennas over a wide frequency range. As the platforms play an important role in the performance of the antenna, development and enhancement of powerful tools to optimize the location and performance of the antenna on a platform. This tool should be fast and efficient to be able to work on a desktop PC."

"Fast solvers, optimization, efficient and integral geometry generation."

"Fast solvers."

"Fast solvers."

Techniques are needed that will accelerate the solution process without degrading accuracy to a questionable level. It is essential that the numerical mathematics community examines our various approaches to the solution of EM antenna problems and suggests ways to accelerate these solutions. In the process, it will also be beneficial to establish estimates for approximation and round-off errors.

Another important area, which is mentioned twice in the above table, is optimization,

"With so many powerful analysis codes available, I suggest to start the development of synthesis codes. It will allow a non-antenna engineer to design antennas with a set of given system requirements. The current analysis codes still require antenna experts to effectively use them. Software code similar to Genetic Algorithm should be the direction to go."

"Optimization."

"Design (perhaps the most important effort) with specific goals in mind."

"Optimizers."

"Design methodology…. code usage is not currently very cost effective."

There is little doubt that optimization will play a significant role in antenna design software. As we pointed out in Section 4, however, we should keep in mind that "Design optimization should not be a mathematical problem that leads us to *the* global optimum of some quantity of interest; rather, it should be a philosophy of design that combines mathematical optimization with other processes to arrive at a satisfactory set of design parameters". The "other processes" can range from sophisticated CEM codes to "quick and dirty" approaches that will bring us within striking distance of satisfying all the design requirements,

> "I can not speak with authority here, but here are my thoughts. In all scientific and engineering fields, there are a great number of analysis codes. However, there is a lack of good design tools. A design code and analysis code are two very different beasts. Design codes often employ a mix of empiricism and theory. Rarely are the exact equations solved. However, good analysis codes are also needed since in the end the design tool must be verified. Sometimes you get stuck using the design tool and have to use an analysis tool to figure out why the design tool is failing. But design is an iterative, an interactive process. You need to go back and forth between the two types of tools easily."

The second item that appeared two tables ago was efficient and integral geometry generation. This need is echoed by others,

> "CEM community in general and ACEM community in particular lack dedicated mesh generation tools geared towards ACEM analysis tools. Currently geometrical and meshing packages are borrowed from other disciplines (Computational Fluid Dynamics, Computational Structures etc.), to be used with CEM codes. Development of a geometry and meshing tool for ACEM codes will enhance the power of these codes to a great extent. It will be worthwhile to either develop or modify existing tools to suit the needs of ACEM codes."
>
> "Geometry generation."
>
> "Improved geometry/meshing tools or additions to existing CAD programs—also include data display."
>
> "Investigate issues concerning use of CAD models in ACEM codes (geometry representation and repair, extraction of high-order geometric data, meshing, etc.)."
>
> "Automatic meshing."

Geometry generation and meshing is *the* Achilles' tendon of CEM and ACEM. The reason is not that it is an insurmountable problem but that not enough attention (money?) has been paid to it. Many problems arise in the course of generating geometry for a specific CEM/ACEM method. The most common problem for older platforms is that CAD drawings do not exist and engineering drawings are not readily available. This is a serious situation when trying to mount new antennas on older platforms. It is not easy to get around this problem, especially when the platform is geometrically complex and a high-fidelity model is required. Solutions range from creating simplistic models using basic dimensions of the platform to accurate ones using laser, and other, mappers.

Even when CAD drawings are available, they may not be what the particular CEM/ACEM computational engine requires. Modifying the available information to the kind of mesh required by the code and "cleaning up" the resulting model, so that it will not cause the numerical algorithms to break down, may require major effort. These kinds of activities need to be automated as much as possible. The time required to produce a model for a specific application should be reduced by an order of magnitude in the next three to five years if CEM/ACEM is to become an effective tool.

A good number of suggestions had to do with modeling complex antenna systems,

> "Its still the same, ability to handle very large and extremely complex material embedded antennas."
>
> "Antenna system size is on the order of 30 by 30 by 2 wavelengths."
>
> "Antenna arrays of complicated elements, especially finite arrays containing 100 - 2500 elements."
>
> "Exact methods to treat large finite arrays embedded in materials."
>
> "Another research area demanding more attention is the modeling and design of antennas based on complex materials. Examples are lens-based antennas, chiral antennas and antennas with magnetic, biased, ferroelectric, anisotropic substrates, etc. Developing general-purpose codes for the analysis and design of such antennas will be pivotal for the advancement of next generation antenna systems."
>
> "Broadband Antennas."
>
> "Improve impedance predictions of various antenna types."

Besides getting involved in ACEM, one suggests that the EMCC should also play a leading role in promoting advances in antenna technology,

> "It seems that the main objectives so far are related to software (code) development. This basically parallels what the EMCC did/doing for scattering; nothing really "earth shaking". I believe that the EMCC should also play an advocacy role in innovation and advancement of antenna technology. If we do not advance and innovate, we will not have anything to apply the developed software. Wireless communication is in need of innovation of antenna technology (for example, smart antennas). Are there similar innovations and advancements?"

We think this is a fine suggestion and the EMCC will consider it in its weekly meetings. It will probably require a survey as the present one.

Another participant suggested that, for the next three to five years, we should also make a point of developing,

> "Benchmark problems."

This is one of the priorities of the EMCC. We have been involved in building and maintaining an expanding database of benchmarks for EM scattering problems. We are about to do the same for antenna problems. We invite all persons interested to participate in creating this new database. We will accept challenging antenna structures, and measurements and/or predictions of their behavior.

A number of other topics were suggested as good research areas for the next three to five years. Among them

> "GUI's."
>
> "Post processing."

and emphasis on some method or other

> "Time Domain."
>
> "Need to develop a user friendly Finite Time/Frequency Difference codes for parallel architectures."
>
> "In general we believe the Full-Wave solutions are the only calculations that can be relied upon to produce accurate antenna parameter results. To get to the next order of antenna problem size, the frequency-domain Nyström formulation for integral equations (Wandzura, HRL) seems to be one of the more promising solutions when combined with a fast solver such as FMM or AIM. Extensive research into singularity extraction has been and will continue to be priority for large problem solution convergence. Among time-domain formulations, FDTD is more of a brute force technique although modified grid techniques will make it more efficient. Finite-volume and characteristic-based equation techniques (Shang, WPAFB) appear to have greater potential for efficient solutions."
>
> "Well, of course, methods like fast multipole and FE will, and should, get a lot of attention. I believe, however, that the HF techniques still have an important role and some effort should be devoted to them. Extending these techniques to work in environments comprised of various materials will, I am sure, not be the "principal thrust of ACEM research," but to me this seems an important and challenging problem."

The importance of having a variety of codes, each with a different computational engine, is stressed in the following,

> "I think it would be a good idea for antenna code development to continue simultaneously in the areas of MoM, FEM, and FDTD. In each case, the incorporation of a user-friendly GUI is essential. The availability of several different types of codes, using different types of computational engines, will give users a choice of approach that is the most appropriate for their particular problem. Having a suite of codes available is also important for verification purposes. An example of this is the company Zeeland Software, which markets two different products, one based on Mom (IE3D) and one based on FDTD (Fidelity)."

Finally, one person makes the point that we should not be discussing this matter at all and that, maybe, we should let the free market forces determine what kind of research will take place in the next three to five years,

> "This is hard to answer. The market for antenna CAD software is relatively small, but commercially available software is beginning to be produced with increasing capabilities, and there seems to be enough demand from users to support a number of vendors. In this sense, then, the marketplace will likely produce the best product, in terms of ease of use, availability, and features – things that are not likely to be enhanced by government or organizational meddling. On the other hand, research money could be provided by the government to support R&D into improved algorithms and more basic types of investigations. After all, the present EM software industry largely evolved from work done in academia, as supported by NSF and DoD funding."

We must bear in mind, however, that we are not talking about the commercial market in this report but mostly about the needs of the DoD. Even if these needs do play the role of market forces, what we are trying to accomplish is to anticipate them well ahead of time. This way the necessary tools will be in place when the DoD needs them.

This concludes the analysis of the responses in Part IV of the survey. It turns out that hybridization, fast and efficient methods, optimization, and complex antenna/array design turn out to be the greatest concerns of the respondents.

Section 7. Part V of the Survey: Impact of ACEM Software

In this part of the survey, we posed the question "What areas of your business, research, or technology does ACEM impact and to what degree?"

The responses can be found in raw form in Appendix E. We arranged these into three categories: academic, governmental and industrial.

In all three categories the responses were on the enthusiastic side. We begin (in alphabetical order) with what the academics had to say.

7.1 Academic Responses

As expected, some emphasized the importance of ACEM in research activities,

> "From a research point of view, ACEM is very important for advancing new technology. Having good computational tools available will free researchers from the burden of spending an inordinate amount of time developing in-house programs and analysis techniques in order to analyze new antennas that are proposed. Having good ACEM tools will allow researchers to devote more of their time to designing new antennas and testing their ideas for novel antenna designs with "virtual experiments", rather than developing specialized analysis tools or performing costly measurements. This translates directly into increased productivity for achieving revolutionary antenna designs in areas such as wireless communications, where the antenna are often sufficiently complex that ACEM tools are mandatory."

while others in education,

> "Education."

The case for research is made very well. In teaching, ACEM tools can play an invaluable role in helping students understand how antenna fields behave. Moreover, on a more advanced level, one can envision antenna courses designed around ACEM tools to teach students realistic antenna analysis and design. This makes an excellent case for a good GUI and good pre- and post-visualization tools. In this context, one might be able to attract NSF's attention as a funding source for course-related ACEM development.

Some academics lament the lack of support on the part of the government and the industry in developing CEM and ACEM tools,

> "I would say that the software I have developed has been an outgrowth of basic

research that was supported by federal funds. Such funding has all but stopped, so it is likely that progress in computational EM will also level off, while the problems that need to be considered from a CEM viewpoint are increasing in number and difficulty."

"Previous and traditional efforts in CEM and ACEM have been driven by specific project applications and needs. Also, antenna design was primarily done experimentally with little or no simulation in the loop.
Currently there are lots of software for narrow band antennas, but no software available (except for home grown Univ. codes) are available for designing future multifunction antennas. The lack of support for FSS design tools is a more puzzling issue. FSS have been developed since the 1970s. However, to this point, the more powerful FSS analysis tools have only been designed as an outcome of antenna needs. This is an example that may be interpreted as lack of interest. However, when compared to existing/established efforts in CFD and Computational Mechanics, the lack for similar efforts/interest in CEM and ACEM is puzzling. A possible explanation is that DoD companies have had considerable internal research activities that to a great degree were focused on the support of projects. However, today's reality is very different:

1. Only a few major procurement projects are now in the works.
2. These few procurement projects require high tech efforts and integration which is no longer available in a single company.
3. The usual cycle of 10 years or so to develop a new platform has been replaced by a short term 3-year plan. In this case, success depends on the availability of software design tools which will shorten the test and evaluation as well as implementation cycle.
4. The maintenance of large research groups with specialized expertise within the large organizations is a thing of the past.
5. We must now rely on multidisciplinary teams put together for a short period of time for delivering a specific product or platform. The availability of general purpose design tools with an integrated approach to design is the most likely future direction. In many cases, these tools must be used by engineers from other disciplines. Thus, design loops will play a major role and must integrate different criteria from different disciplines.

All this, makes the need for a concentrated government effort for CEM and ACEM very timely and crucial. Europe's commitment to such design tools is perhaps another example that we should follow. CATIA today is used throughout our industry. It is a French package that has the reliability and quality not offered by American gridding packages. The reason is mostly due to funding consistency and not to any technical advance contained in CATIA and which does not exist in the comparative American gridders.

Some other arguments:

–Antenna coupling to electronic systems is a new issue that must be addressed today

–Multifunctional antennas makes antenna design a more complex process."

These responses summarize well why it is to the interest of the government to fund ACEM work independently of other, hardware oriented, projects. As one cautions, however, this involvement should be with an end product in mind

"There are many centers of excellence of antenna technology. The government should look very carefully which are these centers of excellence that actually do deliver and not put on the efforts on some very generic research efforts that ultimately are very academic and have no practical use."

Finally, we have the suggestion that,

"EMCC has not so far made a case to the society to exemplify that antennas are an important integral part of life. Without it, no system is going to work well. Demonstrate to the appropriate powers that an improvement of the design in an antenna can reduce the system power requirements and thereby making the devices more compact and efficient than ever before."

We may be guilty of being rather slow in entering the ACEM arena. We intend, however, to make a strong case to the government as to the importance of ACEM software as an analysis and design tool; indeed, this is the primary reason for this survey.

7.2 Governmental Responses

There is no doubt as to the significance government engineers attach to good ACEM tools. Some express these thoughts in general terms,

"ACEM is a critical aspect of how we are and will be doing business. We are asked to solve problems of antennas on aircraft, helicopters, and other specialized structures. We perform both measurements and computational models. But, when it comes to performing "what if" studies, as well as concept developments, physical models and measurements become almost obsolete due to the exponentially increased time and expense needed to perform such measurements. On the other hand, computational modeling serves as an excellent quick, accurate, and relatively inexpensive way to perform the task at hand."

"Having the proper ACEM tool(s) at hand is critical to the success of our mission. Not having such tools forces us to use inefficient modeling techniques, which

> would impact our productivity and the accuracy of our results. Also, we are sometimes forced to model only a portion of the model at hand, thus never realizing the effect of the full structure on the performance of the antenna(s) at hand."

while others provide details about projects that are impacted by ACEM,

> "The IIT Research Institute staffs the DoD Joint Spectrum Center (JSC), which is tasked to provide guidance throughout the US DoD with regard to issues of EMC and electromagnetic interference (EMI). Our requirement is for computationally efficient, user-oriented, ACEM software that can support analyses of EMC/EMI in aircraft, shipboard, and other environments. HF codes, such as our AAPG and the Ohio State University's Basic Scattering Code, have been used extensively because they are fast and provide a level of accuracy that is satisfactory for our purposes. Antenna modeling is frequently performed, and the NEC model has received particularly wide use. The JSC has expended considerable internal resources in code development, and has procured a wide array of externally developed codes. The goal has been to provide products that meet the needs of the IITRI/JSC internal user community, which is, by and large, comprised of people who are not ACEM experts."
>
> "RF Sensor Technology:
> 1. Foliage Penetration Radar (SAR, GMTI, EW): utilizes low frequency (VHF-UHF) wide bandwidth scanning arrays, where complex 3D elements are required to achieve the band coverage. The array edge effects are substantial, as are the platform interactions. Full wave analysis of platform effects is computationally intensive, and use of diffraction techniques is questionable.
> 2. Large phased arrays for surveillance and tracking, airborne SATCOM.
> 3. Small conformal arrays on platforms for GPS."
>
> "My job is to look at ways of integrating electromagnetic requirements into the aircraft design process with a view towards optimization. Immediately everyone thinks of stealth, which is what I am currently working on. However, the people I work with are involved with an ISR platform (Intelligence, Surveillance, Reconnaissance), which is basically a big flying antenna. There are a whole host of antenna-platform integration issues given that the antenna and the aircraft are really one structure. Sometime within the next year I hope to begin looking at antenna integration on air vehicles. For me and my organization, ACEM would impact mostly the front end of the design process (conceptual design). Of course we do some detailed work as well such as wing and fuselage design, which could be influenced by antenna requirements at a more detailed level."

Some responses were not as detailed; nevertheless, they provide good information,

> "Antenna design, development, and research for spacecraft technology will be impacted by ACEM."
>
> "We are heavily involved in shipboard, aircraft, and space phased array design and application."
>
> "ACEM has provided us the tool to demonstrate wideband antenna technologies for shipboard applications (AMRF)."
>
> "The Air Force has wide needs for antenna design tools."

Looking at the information above, we can find every application imaginable where ACEM could play a critical role. From antennas on ships, aircraft (inhabited or not), and satellites to EMC, EMI, SAR, GMTI, surveillance, reconnaissance, and on to a practically endless list.

We conclude here with a recapitulation of the principal assets of ACEM in government-related engineering projects,

> "Efficient, accurate and cost effective way to design antennas!"

7.3 Industrial Responses

Here we have some general comments about the significance of ACEM in the design of present and future systems,

> "Advances in ACEM are essential for design of the next generation of aerospace vehicles. Antennas are simultaneously becoming more complex and more mission-critical. In particular, development of effective and survivable unmanned vehicles will require better antenna design and analysis software than is currently available."
>
> "Aircraft and missiles have a variety of antennas of different types and for different purposes, and it is important to predict the installed antenna performance and coupling with other antennas on the platform."

but also comments that describe in-house activities,

> "Our business deals in Countermeasures (ECM and ESM) and SIGINT. Our systems cover frequencies from MF to 96 GHz. We have a need for very broadband

antennas for the countermeasure systems and high gain, efficient antennas with moderate instantaneous bandwidth tunable over a wide operational bandwidth for the SIGINT systems. Many of our ESM systems do precision DF and hence require broadband, phase stable antennas with predictable phase slopes. Our DF systems oftentimes require expensive calibration, where large portions of a platform needs to be constructed with apertures installed to make the measurements. Of all our business areas, the DF group has the greatest need for good modeling tools that can accurately predict installed performance in terms of phase, polarization, platform effects, mutual coupling, etc. Other business areas desire antenna designs and better performance. The need for ultra accuracy is not as great there since their major concern is interaction or mutual coupling between systems.

Sanders has three antenna design departments with emphasis in DF, broadband CM apertures for aircraft, and Low Observable Apertures for all platforms. The DF group covers frequencies from MF to K-band. The CM group concentrates on UHF, L-, S-, C-, X-, Ku-, & Ka-band antennas. The LO group concentrates on all bands with emphasis on array and aperture antennas. This group designs apertures that cover VHF through W-band for installation on aircraft, ships, submarines, and ground vehicles. The number of antenna engineers in the company exceeds 100 people.

Therefore, antennas are a vital part of our business. They form the eyes to many of our systems."

"The main areas of business at Matis, Inc. are research and development of new fast and accurate methods for predicting performance of antennas mounted on complex platforms. This is a critical technology for DoD and civilian agencies and industries."

"1. Applied EM Inc. is poised to launch a commercial antenna development tool and greatly depends on the development of fast algorithms for antenna analysis. These techniques will make our software work with less memory and CPU time and hence speeding up the design cycle.
2. It is our experience that powerful analytical techniques have to be packaged with a user friendly graphical user interface (GUI) to be productive for an antenna designer. Development of sophisticated GUI with pre and post processing tools is critical for the success of our antenna analysis software tools.
3. An integrated geometry and meshing package tailored for antenna analysis tools is also crucial for the success of our software tools."

"EMAG Technologies is involved in the development of both software and hardware for antenna systems. On the software side, we develop electromagnetic CAD tools based on advanced modeling techniques with user friendly interfaces. On the hardware side, we are involved with the design and prototyping of novel antennas for various communication and sensing applications. Examples include integrated multifunction antennas for automotive communication and navigation, wireless and millimeter wave sensor applications.
As antenna designers, we desperately need more powerful antenna CAD tools to

reduce the costly design cycles. For example, in the design of antennas for automotive applications, an understanding of the interaction of the antenna with the vehicle environment is critical. We have to develop in-house codes for such purposes. As antenna software developers, we are constantly trying to bring some of these codes to commercial use. The major challenges on the way of commercial development include general-purpose (and not project-oriented) engines, easy-to-use interface and rigorous testing."

These comments are not unlike the ones we encountered in the government group and re-emphasize the central role that ACEM will play in near- and long-term DoD critical technologies.

Section 8. Part VI of the Survey: Funding Sources

For it takes money, and without it nothing of what must be done can be done.
Demosthenes, First Olynthiac, 349 BC

In Part VI, the last part of the survey, the participants were asked to suggest appropriate funding agencies for this effort.

The responses can be found in raw form in Appendix F. Most participants point at one or more government agency as the appropriate source of funding. The reason is simple,

> "Because of the high-risk R&D involved in ACEM, the Government should be and will remain the principal funding source. All branches of DoD are somehow involved with ACEM, and DARPA can be a good source of funding due to the advanced and exploratory nature of the effort."

Some, however, are rather pessimistic regarding the prospects of funds being set aside exclusively for ACEM projects,

> "Suggestion of appropriate funding agencies is probably irrelevant. AFOSR and ONR will never be interested in putting in real world enhancements because they are not aware of the shortcomings of available codes. The reason for this is that they neither use such codes, nor do they take inputs from users. Useful developments can and will only come about as the result of a demand by users, and providing feedback directly to the developers."
> "You need to form a group who will present the case to the politicians. Now research is done in congress and it is no longer being done in an university!"

One suggests the generation of a pool of money from program managers,

> "Get several PMAs to support and commit a 3 year funding for the ACEM."

This is an excellent suggestion. Those in charge of programs in which ACEM can be used to advantage may be the ones most willing to commit funds to such an effort. One, however, must first get their attention and present the facts to them, namely, what the state of the art is and where we would like to go; what they can accomplish with today's tools and where our vision can take them. This is not an easy matter. From personal experiences, it appears that the consensus among managers is that the area is already well funded.

Another group of equally influential people who can turn the tide in favor of funding ACEM projects are all those in federal agencies who either support research at various levels or support hardware development that is in need of ACEM. Several such agencies were mentioned in the survey. They are listed alphabetically below,

- DARPA
- DoD
  - OSD
  - Army
    - ARL, ARO
  - Air Force
    - AFOSR, AFRL
  - Navy
    - NAVAIR, NAVSEA, NAWC, NRL, NSWC, ONR
- DoE
- DoT
- NASA
- NSF

Of these agencies, the leading role in ACEM development undoubtedly belongs to the DoD. In all, however, one can find people who understand the importance of ACEM and who are on our side. We hope that this report will add to their ammunition.

One agency that has not figured prominently in CEM and ACEM is NSF. As one participant points out they have supported research (centers of excellence?) in mesh generation for CFD and Structures but not for CEM/ACEM. Maybe the proper perspective has not been presented to the NSF. Not only is CEM/ACEM on a par with any other computational area in terms of number and difficulty of problems, but it may be argued that it is at the very top. Unfortunately, the mathematical statement of the basic scattering or radiation problem appears deceptively simple in comparison, say, with the Navier-Stokes equations. To the uninitiated, this creates the impression that the scattering/radiation problem is trivial compared to problems in other areas, as it indeed happened a decade ago among some members of the CFD community.

NSF can help in many aspects of basic research in ACEM. It can also help in the development of special ACEM tools to be used in teaching antenna courses. Numerical analysis of radiation problems, accompanied by good visualization tools, can enhance and accelerate a student's understanding of complex antenna theory concepts.

Finally, mention was made of the private industry (especially, airline and automotive) as a possible source of funding for ACEM activities. We believe there are very many civilian areas where ACEM can contribute. We are not quite sure, however, whether EMCC could or should get involved in this direction.

Section 9. The New ACEM Toolbox, Research Recommendations, and Action Items for the EMCC

We present here the new ACEM toolbox. We also summarize the research recommendations made by the participants (Section 6) and present some action items for the EMCC.

The toolbox is based on the TWGA Toolbox but modified and enhanced by the responses to the survey.

ANTENNA AND ANTENNA-PLATFORM INTERACTION SOFTWARE TOOLBOX

The Government Executive Committee (GEC) of the Electromagnetic Code Consortium (EMCC) believes that the next natural step in the evolution of CEM software is the development of a toolbox of codes that will significantly contribute to antenna design and antenna-platform integration issues. To this end, the GEC Technical Working Group on Antennas (TWGA) polled part of the antenna community in the Spring of 2000 and, from the responses, it developed a set of desirable features for such codes. They are described below.

I. ANTENNA ANALYSIS AND DESIGN TOOLS

A. TYPES OF ANTENNAS

On the antenna analysis/design side, the toolbox will contain a number of codes, each capable of dealing with one or more types of antennas. The antennas can range from simple wire antennas to arrays of elements embedded in complex, layered media that may not be planar. Examples of antennas are:

1. Wire type antennas (dipoles, Yagis, etc.).
2. Plate (patch) type antennas (notches, reflectors, etc.).
3. Wire-plate type antennas (short backfires, corner reflectors, etc.).
4. Cavity-backed dielectric/ferrite-loaded antennas.
5. Composite metallic and dielectric antennas.
6. Wideband radiators (spirals, flared notches, etc.).
7. Antennas and antenna arrays in layered media (including dielectric layers, R-cards, FSS layers, etc.).
8. Finite but large antenna arrays (linear and otherwise) made of elements as above, especially conformal arrays and arrays in cavities.
9. Infinite periodic arrays.

This list provides a sample of antenna types and is neither exhaustive nor exclusive.

B. COMPUTATIONAL ENGINE ATTRIBUTES

ACEM codes may use more than one computational engine. Depending on the objectives of the code, each engine should possess one or more of the following attributes:

1. Use fast and efficient numerical algorithms. A code should provide options for trading speed for accuracy, either by employing more than one computational engine or by adjusting parameters within one engine. At its most accurate, an engine should be capable of providing correct antenna near-field information (e.g., input impedance) if it is designed for the purpose.
2. Realistically model feeds, connectors, loads (concentrated and distributed), etc.
3. Accurately model complex materials (including lossy conductors and dielectrics, R-cards, FSSs, photonic materials, micro-electromechanical systems (MEMS), etc.).
4. Take advantage of planar and rotational symmetries.
5. Accurately compute all mutual-coupling effects.
6. Accurately account for the presence of infinite layered structures.
7. Incorporate matrix (dyadic) boundary conditions and higher-order impedance boundary conditions.
8. Perform parametric sweeps in terms of various geometry and material parameters for design, optimization, and sensitivity analysis.
9. Optimize quantities of interest with respect to geometry and materials. Trade-off (Pareto) optimization is desirable. If the optimization code is not an integral part of the ACEM engine, the two should communicate seamlessly.
10. Compute all quantities of interest (input impedance, gain, embedded element patterns, array scan impedance, array patterns, etc.).
11. Account for moving objects, such as the rotating wing of a helicopter.

This list is not prioritized.

C. GENERAL CODE ATTRIBUTES

1. Generate geometry or accept geometry in a number of formats.
2. Provide a grid generation tool that does a creditable job in preparing a mesh for a specific computational engine, and/or
3. Communicate with an external mesher expressly designed for the type of computational engine in question.
4. Post-process results efficiently and effectively. Full graphing capability, including simultaneous display of results of parametric sweeps.
5. Run on several platforms and on parallel as well as sequential architectures.
6. For a specific platform, provide a GUI that will guide and warn the user on every aspect of the input process.
7. Contain specific examples (input files) to verify correct installation and function of the software, and provides illustrations of special features in the code.
8. Contain high-quality documentation in electronic form. Documentation should include an instruction manual and an interactive help section.

This list is not prioritized.

D. EXAMPLES OF COMPUTATIONAL ENGINES

1. Wire-type method of moments (MoM) codes (e.g., NEC) for use with wire-type antennas.
2. Patch-type MoM codes (e.g., PATCH) for use with antennas that are best modeled using patches.
3. Wire-patch MoM codes (e.g., EIGER, WIPL) for use with antennas that are best modeled using both wires and patches.
4. Finite-element (FE) or finite-difference (FD) codes for antennas in bounded, layered media.
5. High-frequency codes, primarily to be used in hybrid codes (see Part II, below) when electrically large platforms are present.

II. ANTENNA-PLATFORM AND ANTENNA-TO-ANTENNA INTERACTION TOOLS

A. It is well known that the electromagnetic characteristics of an antenna can be greatly altered by the platform on which it is mounted. Since most antennas are add-ons to a platform (rather than having been designed for a particular platform and a specific location on it), then it is necessary to have appropriate software to compute the interaction of the antenna with the platform, as well as with other, neighboring antennas. If the platform is electrically small, we can accomplish this with a MoM code. This is done today for simple antennas. If the platform is large, however, then we need a *hybrid* code. The antenna and its immediate environment will be modeled by an exact code, while the rest of the structure by a HF code. How the two will interact and how many times the results must be iterated (if at all) is a question that requires substantial research effort. This is especially true when there is more than one antenna present.

B. In the future, we will see platforms with antennas structurally integrated in them. The region in which these antennas will reside will have the general shape of a cavity and will be complex, both geometrically and materially. An exact-type code will have to be used in the cavity. This code will be coupled to the outside through another exact code if the platform is small. If the platform is large, then an exact code may be used for the immediate region surrounding the cavity and a HF code for the rest of the platform, or just a HF code for the entire platform. Since the antenna will be an integral part of the platform, we have the opportunity to design it *in situ*, that is, considering the whole platform from the outset.

C. The codes we have sketched here will be of the same kind as those used to design antennas. The principal difference will be in coupling together codes that are based on different methods. As we just indicated, we may have to integrate up to three codes to account for the properties of a structurally integrated antenna.

We conclude this section by summarizing the near-term research recommendations made in Section 6. Let us first note that good software is needed for all kinds of antennas. As some participants pointed out, a lot of antenna software already exists in one form or another. Most of it is written for specific antenna types. It would be beneficial if a sum of money were to be set aside to identify these codes and put finishing touches to them, that is, make sure that they satisfy at least some of the recommendations made in Parts II.B and II.C of the new toolbox. This is more along the lines of development.

For near-term research (next three to five years), from Section 6 we compiled the following list,

Near-Term ACEM Research

— Hybridization (Interaction of antenna with a large platform in presence of other antennas).
— Fast solvers (For any kind of computational engine).
— Optimization.
— Grid generation.

To this, we hasten to add that the principal focus of the funding agencies should be the creation of *tools* rather than research papers. *We need codes that will enable the antenna designers achieve their goals*. Thus, the aim should be to encourage pushing the frontiers through research but also to spend money on code "peripherals" and on integrating research results into existing codes.

We also wish to add that the list above contains the most often mentioned items. Section 6, however, contains many other topics worth funding as, for example, the problem of the rotating wing or propeller or turbofan, and how it modulates an electromagnetic wave. This problem has been around for a long time but has not received the attention it requires.

The EMCC and the academic community should seriously consider approaching the NSF on both the grid-generation issue and the creation of antenna software for teaching purposes.

Action items for the EMCC, as per participants' suggestions, will be to

— Create a database of antenna benchmarks.
— Discuss the suggestion that "the EMCC should also play an advocacy role in innovation and advancement of antenna technology".
— Approach the IEEE APS about standardization issues.
— Actively promote the creation of the databases of Section 10.

We invite all readers to submit antenna benchmarks. These can be in the form of computed or measured data or, simply, the description of an antenna that is considered a computational challenge. Details on the submission format will appear in the EMCC's web site www.asc.hpc.mil/emcc/. We also welcome suggestions on how to go about creating the databases of Section 10. You may send them to asvestasjs@navair.navy.mil.

Section 10. Databases for Antenna Design

We present here some thoughts on how to improve the antenna design process. They are centered on the creation of databases that can become quick sources of information for the antenna designer. The databases we came up with are the following.

Database of most suitable codes for specific antenna designs. Not every code can deal with every type of antenna. In this database, code designers can supply information about what their code is designed to do well. Code users can relate their experiences in using a particular code with a specific antenna type.

Database of lessons learned from using codes. This database differs from the one above in that users of a specific code can relate their experiences with respect to "bugs", misbehaving subroutines, workarounds, etc. A list of FAQs can be generated for each code. Ideally, another list would contain names of expert users willing to help others. This database could be merged with the previous one.

Database of "quick and dirty" solutions. As we mentioned in previous sections, such quick but approximate solutions may reduce the time required to reach a desirable design by either bringing us in its neighborhood or by serving as an initial solution (guess) in an optimization scheme.

Database of experts on different kinds of antennas. "For we should not care what the many have to say but what the expert", Socrates in Plato's *Crito*. Undoubtedly, sometimes the most economical solution is consulting an expert. Such a database would be invaluable to both government and industry.

Database of antennas and antenna related equipment, including designer and manufacturer information. Although re-inventing the wheel can make us feel good, such a database may help us avoid the after-effects of such a realization.

Database of antenna ranges and their capabilities. There is a lot of variation in antenna range capabilities. Such a database would help designers quickly find the range that best suits their needs.

Database of antenna publications and literature. This database may contain its own list of references but, also, provide links to other databases.

These are some of the databases that may prove useful to antenna designers. Associated with them is the cost of creating and maintaining them. There may also be legal issues to be resolved as, for example, whether they should be accessible to all, and, if not, the manner of their distribution.

Appendix A: Raw Form of Part I of Survey Data

In the following three tables, we display the data from Part I of the survey. Names of participants and place of employment have been omitted. We used these tables to generate the charts of Section 3.

Table A.1. Affiliation of survey participants and capabilities of their workgroup.

AFFILIATION	CAPABILITIES OF WORKGROUP				
A: Academic C: Consulting G: Government I: Industry	Algorithm Development	GUI Development	Grid Generation	Pre-/ Post-Processing	Other
G	X	X	X	X	
A	X			X	
G					X
G	X	X	X	X	
A	X				
I		X	X	X	
C	X				
G	X	X	X	X	
G	X				
I	X	X	X	X	
G	X	X			
A	X			X	
A	X	X	X	X	
G	X		X	X	
G					X
A	X	X	X	X	X
C	X	X		X	X
G	X	X	X	X	
A	X	X			X
I	X	X	X	X	
I	X	X		X	X
I	X	X	X	X	
A	X	X	X	X	X
A	X			X	
G	X	X	X	X	
G					
G					X
A	X		X		X
Totals	23	16	14	18	9

Table A.2. Affiliation of survey participants and their principal function(s) in years (an X indicates that a box was checked but number of years was not stated).

AFFILIATION	PRINCIPAL FUNCTION OF RESPONDENT (Years)					
A: Academia C: Consulting G: Government I: Industry	Analysis and Algorithm Development	Antenna Design	Antenna SW Development with Extensive Experience in Antennas	Antenna SW Development with Little Experience in Antennas	Contract Monitoring	Other
G	15	15			15	
A						
G						X
G		30	30			
A	20		5			
I	X	X	X		X	
C	48	48	48			
G	18	18	18		16	
G		X				
I	10		10			
G	17		17			
A	15	10				
A	20	18	18	2		
G	X	X				
G		X				
A	30	30	30			
C	18					
G		X	X			
A	23	19	19			X
I	20			X		
I	10	12	10			
I	X	X	X			
A	25	20	25			
A	25	25	20			
G	15	10	12			
G		X				
G						X
A	22	10	15			
Average Number of Years	20.65	20.38	19.79			
Number of people	20	20	17	2	3	3

Table A.3. Affiliation of survey participants and frequency of using antenna design software.

AFFILIATION	FREQUENCY OF USING ANTENNA DESIGN SOFTWARE		
	Daily	Weekly	Monthly
G	X		
A	X		
G			
G	X		
A			
I			
C	X		
G		X	
G		X	
I	X		
G			
A			X
A			
G		X	
G		X	
A		X	
C			
G			X
A	X		
I			
I			
I	X		
A		X	
A			
G	X		
G	X		
G	X		
A			
Totals	10	6	2

Appendix B: Raw Form of Part II of Survey Data

II. ANTENNA AND ANTENNA-PLATFORM INTERACTION SOFTWARE TOOLBOX
Please give your reactions to the accompanying document bearing this title (open antenna_map.doc). Suggest modifications, additions, and deletions. When appropriate, refer to the sections and subsections there. Use additional space if necessary.
Please note: Each bullet (❖) represents one person.

❖ Response 2.1

—Mutual coupling effects are of great importance to me.
—Most antenna synthesis codes work from currents assumed known in the antenna structures. I recommend increased development of codes that work from the source to compute current induced in the antenna and resulting radiated fields.

❖ Response 2.2

—Antenna-to-Antenna Interaction on the Same Platform (Cosite Interference); very critical problem when multiple antennas are mounted on the same platform (which is usually the case in most cases).
—Cavity-Backed Dielectric/Ferrite-Loaded Antennas.
—Rotor Modulation.
—Should also address antennas for wireless communication.
—Frequency ranges should also be mentioned in some of the applications. There is a need for good antenna designs for HF, VHF, UHF and Wireless Communication.

❖ Response 2.3

—I.B. Such codes should have the ability to

1. Use the latest numerical algorithms for speed and accuracy.
   Not necessarily. I believe there is a need for conceptual design tools, which need to be really fast perhaps at the cost of accuracy. Perhaps some empiricism would help. In terms of a conceptual tool, I mean a code that would quickly let you know the best place on the structure to put the antenna and maybe a guess at size and weight. A conceptual tool with these capabilities could be integrated with conceptual tools from other disciplines (if you are building airplanes then these disciplines would most likely be structures and aerodynamics).

2. Optimize quantities of interest with respect to geometry and materials. Trade-off (Pareto) optimization is desirable.
   Yes, yes, a resounding yes. Of course I am in the optimization business, but this is exactly the type of thing you want to be doing as early as possible in the design process to reduce design effort and costs and increase performance.

3. No comment

4. Accurately model complex materials (including lossy conductors and dielectrics, R-cards, FSSs, photonic materials, micro-electromechanical systems (MEMS), etc.).
   If these materials are used and are of benefit, then yes. This would fit in well with #2. Also if the antenna is going on an airplane, these materials affect cost. In today's business environment in aircraft design, weight sometimes takes a back seat to cost. This was not always the case. During an optimization process, the algorithm might choose a material with less performance because it costs less or has lower life-cycle costs associated with it.

5. Take advantage of planar and rotational symmetries.
   Yes. Anything to speed up the analysis.

6. No comment.

7. Store impedance matrix of a structure for later use in a geometrical arrangement that involves this structure in addition to another (numerical Green's function in NEC).
   Yes. This allows pieces to be analyzed separately. This is something that you really want to do in design, especially conceptual design. This would be of great benefit for air vehicles. Aircraft tend to get analyzed in pieces early on. Used with a HF code, this would allow an aircraft to be analyzed without having to put all of the details into one model. Keep It Simple Stupid.

8. No comment

9. Accurately compute all mutual-coupling effects.
   If you are making a design tool, then only if it affects the overall design. Otherwise put this capability into an analysis code. Mutual coupling can only dramatically increase run times.

❖ Response 2.4

—The types of antennas and environments could be broadened. Dielectrics, both homogeneous and inhomogeneous and grounds that are irregular on a small or large scale should be included. FE or FDTD with a generalized wire modeling capability could be applicable for these problems.

—The inclusion of optimization near the top of the list is ambitious. Simply designing the code I/O so that it is reasonably easy for end users to develop their own interfaces, for example to visualize results on various slices through the parameter space, would be very valuable. That is, unless the supplied pre/post-processor is complete enough to do everything the user might want.

—The Numerical Green's Function capability in NEC does not seem to get used much (item B7). It would be more useful with what has been called "concatenated NGF", where an inverse or factored matrix would be updated to produce a new inverse or factored matrix with elements added or subtracted from the structure. Error propagation might me an issue here though.

—Iterative and sparse matrix and other methods for getting numerical solutions for large problems represent an important area for advances needed in future codes.

❖ Response 2.5

—I think the antenna map is great and well-thought out. However, two areas should be emphasized, the ability to model disparate length-scale, i.e., a combination of fine geometry details requiring very fine meshes together with smooth surfaces where coarser meshes can be tolerated. This would eventually give rise to better antenna software for the input impedance of the antenna.
—Another emphasis should be the ability to solve all these problems with the efficient use of memory and CPU time. It is also imperative that many of the reflector antenna software be based on first principles electromagnetic analysis such as the method of moments etc. This is only possible if fast solver technologies be used to develop these software.

❖ Response 2.6

—Many aspects of aperture design have been considered in the document. It is quite inclusive. Most antenna codes usually do well in predicting radiation pattern behavior. However, the majority of antenna codes are also deficient in predicting the input impedance well. One can get an idea of impedance behavior with voltage or current sources, but it is not usually what is measured at the connector. More effort has to be placed in realistically modeling the feed (including the connector). This will have to include the ability to do adaptive meshing in cases with fine structure.
—There is also a need to improve the models, especially using FEM, for cavity type antennas with materials inside the cavities. Several of our codes have had discrepancies between the computed and measured resonant frequencies. The percentage difference can be as off as 5%. We have attributed this to assuming PEC for the walls of the cavities. When we include a skin depth (material/metal losses), the resonant frequencies begin to agree with experiment. MoM codes that utilize full wave analysis do not have as bad a problem, but they are limited to cavities where the Green's function can easily be determined.
—Most non-commercial antenna designs now have RCS requirements associated with them. The scattering codes usually cannot handle antenna scattering. Low RCS apertures require aperture edge treatments, coatings, FSS radomes, etc., that is not modeled by existing codes. Antennas embedded in layered media are a challenge, especially if surface waves and other effects are to be included. A subset of this is a robust code capable of predicting performance of large arrays with low sidelobes or requirements for deep nulls. Such codes exist for pure metal plates with waveguide or cavity type radiators. However, there is nothing very good for embedded arrays.
—All codes are currently too slow for large finite array analysis. The problems stem in system memory requirements and solver speeds. More effort needs to be dedicated to reduce problem size below NlogN to speed up the computation. NlogN is currently state of the art (FMM, AIMS, FSDS, etc. are all algorithms that help achieving NlogN.) Effort needs to be made to reduce it to O(N).
—Meshing (producing geometry) is probably the biggest handicap in utilizing codes. I believe that the CEM community and aerospace industry needs to make it appealing for the major

CAD packages to include surface and volumetric meshing suitable for CEM in their packages. The CEM community should not be trying to reinvent the wheel by creating our own CAD meshing packages for EM modeling. A coherent strategy needs to be developed with commonality between the packages.

—Mutual coupling between antenna elements within the same array is predicted efficiently for infinitely large arrays. There is a deficiency in this area for large finite arrays, especially when embedded in media. Mutual coupling is also a serious RF system issue wrt EMC/EMI. Predicting antenna coupling, radiation patterns, RCS when installed on some platform is a capability that is currently quite limited. Hybrid methods employing high frequency techniques are currently employed to address these problems. However, these techniques leave large frequency bands with questionable results…I am referring mainly to the UHF, L-, and S-band regions where the HF techniques are not too accurate due to large wavelength compared to the size of the antennas and scatterers. Obviously these techniques fail in the VHF, HF bands….but there full solutions are possible unless the platform is very, very large.

—Asymptotic techniques have been beaten to death in the last 30 years. This is not to say that there isn't anything new in this arena. However, we need to concentrate in fast numerical solvers and algorithms.

—Finally, the area where we need to concentrate more is in codes suited for antenna design. Until we get to speeds that produce true real time results, we must develop codes that have approximate to exact methods built in to allow design. The design engineer and the antenna design process cannot afford the hours required to input and wait for exact answers while in the early stages of design. The codes we currently have require a group of PhDs to run them and to interpret the results. We need approximations that indicate trends and major problems in terms of installation location, etc. Once a preliminary design is determined, one then needs the more accurate codes for design refinement. Currently numerical analysis and design takes too long and is too expensive.

—In addition to design codes with varying degrees of approximation to exactness, we need to put more effort into optimization. Final optimization and tweaking can take anywhere from 30 to 50% of the design time. Optimizers are needed (1. impedance (VSWR) & bandwidth, 2. Pattern & sidelobe optimization, 3. RCS reduction).

❖ Response 2.7

1. The objectives outlined in the Antenna Design Tools section seem unrealistically broad.
2. Many of the capabilities described in Sections A and B are currently available, spread across a multitude of codes, with varying levels of user interface sophistication.
3. A large number of the currently available codes are commercially owned and marketed.
4. It seems unnecessary to 'reinvent' capabilities that already exist, especially if thousands of man-hours have been invested (either privately or federally).
5. A modest goal might be to try to improve the pre and post-processing capabilities of government owned software, which tends to have less emphasis on those portions of the code.
6. It would be useful to set a standard input format for 2D and 3D mesh geometries for a number of the government owned codes, including a set of basic feeding methods (delta-sources, coaxial, waveguide, aperture coupled, etc). Comparisons of several analysis approaches would be much easier as a result. Commercially available drawing packages such as PATRAN or IDEAS could be used as a framework for the input formats.

7. As noted in Section B, a standard for the output information would also be very useful.
8. With standardized inputs, it may be possible to develop an optimization shell, whereby a design optimization code is 'wrapped' around an antenna analysis engine. The optimization shell could be general enough to utilize a variety of computing codes, (seeking to optimize the defined output parameters as a function of defined input parameters). Preferably the government-owned codes referred to above would be used as the engines, and the I/O formats would be standardized.

❖ Response 2.8

—The list of desired code capabilities seems fairly complete. While one can conceive of a code which does everything on the list, it is not likely to be the most efficient approach for all antennas. There will always be a trade-off between generality and efficiency.

—As evidenced by paragraph II.B, there seems to be a general perception that the FE method is the best or only way to analyze complex cavity antennas. This may be due to the fact that early MoM codes failed in cases where tiny facets are required to capture geometrical detail. More recent MoM implementations do not fail in such cases and, in my experience, are not only easier to use, but also more efficient than FEM codes. This is because the size of the elements is driven by the smallest geometrical detail causing the number of unknowns to explode if there is an appreciable volume to grid. Of course, a volume formulation of some kind will still be required for anisotropic material.

❖ Response 2.9

—No comments.

❖ Response 2.10

—In paragraph D under II ANTENNA-PLATFORM AND ANTENNA-TO-ANTENNA INTERACTION TOOLS, it is stated that "We are not quite certain we should encourage development of interaction *codes* (italics added) that are based strictly on HF methods." I agree that an end-product HF code devoid of any hybridization would be unduly restricted in applicability. On the other hand, HF algorithm development should certainly be pursued, and not all HF algorithm development will be directly related to the issue of hybridization. To ensure that this distinction is not overlooked, I would recommend changing D to read:
D. HF algorithm development should be encouraged with the understanding that all end-product codes must be able to account for complex antenna structures, presumably via some hybrid scheme.

❖ Response 2.11

—One issue not addressed in this document is user support and support for continued code development. How will this be guaranteed? Should the codes be developed in such a way that outside groups can add to them in the future?

—Another issue is code availability. Will such codes be available as public domain codes, or available only to users working on government contracts? Will they be made available to researchers in the universities? Will source code be made available?

❖ Response 2.12

—The list of capabilities requested is almost complete. However, in our experience with antenna design we have encountered issues with the software only solvable by having the source code available for modification. It is normally not efficient or practical for an antenna software designer to include all of the design features into a single code. Even if a code tries to include all of these features, there will be unforeseen instances that the antenna designer can only circumvent by modifying the code for the particular application. For example, there may be antenna engineers who are accustomed to generating FDTD animations with a graphics visualization package such as AVS. To obtain the outputs from the antenna software to be input into AVS, the source code must be available for modification. Otherwise, the code will become an albatross the original code designer since he or she will be bombarded with code modification requests. Supplying the source code for the antenna-platform calculation engine as well as the GUI software is the most efficient way of realizing antenna designs, although proprietary agreements may then be necessary.

❖ Response 2.13

— Obviously, this list I.A is far away to be complete… In my opinion, very important is to add:

V. Plate-dielectric type of antennas (e.g., dielectric rod antenna, dielectric resonator antennas, dielectrically loaded horn antennas, etc.) (Another possible name for this class is composite metallic and dielectric antennas.)

VI. Antenna radomes

VII. Antennas at large platforms (This is mentioned later, but not here in the list.)

…probably some other very important classes are missed…

Note: Word 'dielectric' should be understood in wide sense. Namely it is often used instead of word 'material'.

Related with the list "I.A" and partly list "I.B", there is a question: Which are basic types of entities that can be used for efficient modeling of any above-mentioned type of the structure? One possible list is:

1. Point generator
2. wires
3. plates (PEC patches)
4. dielectric patches
5. dielectric bricks
6. distributed loadings
7. concentrated loadings
8. infinite dielectric layers (and halfspaces)

Related with the list I.D and list II, there is a question: Which method, or which combination of methods is optimal? It also depends if we solve the problem in the frequency or time domain. I have no much experience in the time domain analysis. Hence I will give the answer only for the frequency domain analysis. The answer that I will give is biased by the fact that I am most familiar with MoM. (Actually on a scale from 0 to 10 my marks are: MoM-10, FEM-3, FD-2, high frequency techniques-3.)

I see the MoM as a basic technique for solution of composite metallic and dielectric structures. When applied to BIEs it enables user to solve almost any problem of maximum dimension of 10λ at the PC computer. Many larger problems (10λ-100λ in maximum dimension) can be also solved at the PC, particularly, if symmetry properties can be taken into account. Only a few problems whose maximum dimension exceeds 100λ can be solved at the PC.

In the case of antennas mounted on large structures (greater than 10λ-100λ), the MoM should be hybridized with high-frequency techniques.

The MoM-BIE can not be applied to anisotropic and bianisotropic media. In that cases the MoM should be hybridized with the MoM-VIE or the FEM. Hybridization with the FEM can also speed up the analysis of highly inhomogeneous structures.

Let us conclude:
The MoM-SIE is recommended as a basic technique for solution of composite metallic and dielectric structures. It should be hybridized with:

1. High frequency techniques for electrically very large structures
2. MoM-VIE or FEM for anisotropic (bianisotropic) and/or highly inhomogeneous media.

❖ Response 2.14

—Very comprehensive WISH list!

❖ Response 2.15

—No comments.

❖ Response 2.16

1. I agree with the philosophy of hybrid codes as stated in SECTION II, part A. However, the option for fast modeling of electrically small antennas should still be available.

2. While the HF methods for calculating scattering have been around for some time, only recently, new methods significantly expanding their capabilities and precision have been discovered (AAPG, DOVA, CDOVA, Xpatch, though the latter one is an RCS code). This suggests that excluding development of HF interaction codes is a wrong thing to do. (Fast Multipole Method (FMM) could have been a victim of such "exclusion" less than 10 years ago!) The statement in part D of SECTION II is not proposing a strict exclusion policy, but it is quite strong. For example, I think that developments leading to utilization

of CAD models of platforms by HF-based (and other CEM) codes are critical and should be encouraged.

Connected with the issue discussed in 2 are the issues of geometry representation, meshing, and use of CAD models by CEM codes. CAD models are widely available, but almost always have to be pre-processed before they can be used by computational codes. This is a currently a major issue in applying FMM-type solvers (as well as other codes). One also needs to remember that different computational codes have different geometry requirements and the philosophy "one-size-fits-all" is not likely to work here. Hence, adding to SECTION II a topic concerning platform geometry representation and related issues seems quite appropriate.

❖ Response 2.17

—The Navy has an ambitious program on going out of ONR and NAVSEA (DD21) offices.
—ONR has a BAA contract in execution which addresses this area.
—DD21 's VIPER program is looking at current technology in this area.

❖ Response 2.18

—I believe antenna CAD is best implemented by a *suite* of packages that are tailored to specific antenna geometries. For example, wire antennas are best treated with moment method techniques, in terms of entering problem geometry, computational efficiency, and interpretation of results. A finite element program (eg, HFSS) can also handle wire antennas, but it is difficult to specify the input geometry with HFSS, and it is much slower in terms of cpu time. Similarly, microstrip antennas are best treated by moment method solutions using Green's functions for dielectric layers, and are not handled very well with finite difference or finite element methods. On the other hand, finite difference and finite element packages can treat very general problem geometries, espcially when inhomogeneities are present.
—The marketplace for antenna cad is, of course, evolving in this fashion, and there are commerically available packages for specific types of antennas. **Momentum**, **Ensemble**, and **IE3D** are useful for microstrip antennas. **GRASP** and the **OSU code** are good for reflector antennas. **HFSS** is useful for other types of problems.
—The question of modeling structural interactions is difficult, because it is rarely possible to rigorously model both an antenna and its structure completely. In addition, the large number of structural geometries of practical interest, multiplied by the number of possible antenna geometries, leads to such a large variety of possible combinations that it seems to be impractical to expect packages to be able to accommodate such variety. Instead, I think it will be necessary to use a specialized analysis code for the antenna, and couple its output to a GTD, GO, or PO type analysis. One way to facillitate this approach would be to propose a standard form of output from antenna analysis packages for use for standardized GTD codes.
—Another application that many of the workers in the ACEM field largely ignore is the analysis of phased arrays and frequency selective surfaces. Often these problems require spectral domain solutions for infinite arrays, and are very specialized. I have sold many 'one-off' codes like this, so there is a demand for them, but there is essentially no commercially software that addresses this need.

❖ Response 2.19

—I would tend to agree with everything that is contained within that document. In addition though, I think that some sort of "best practices" list should be developed. For antenna designers who use computational EM tools, it would be good to have a resource which would be a collection of lessons learned by others in using different tools and methods.

❖ Response 2.20

—Comments on Antenna Design Tools:

1. Analysis techniques for wire and plate type of antennas are well developed and are widely in use (NEC etc.). But these codes are based on Method of Moments (MoM) techniques and require large matrix storage and CPU time, if the antenna contains fine geometry details or if it is electrically large (for example, high gain reflector antennas). To efficiently analyze such antennas, the MoM based codes should be enhanced with fast algorithms such as Fast Multipole Method (FMM) or Adaptive Integral Method (AIM).
2. Cavity-backed antennas are analyzed accurately using hybrid Finite Element (FE)/MoM techniques. The volume of the cavity with complex materials is analyzed using FEM and the aperture is terminated using MoM. For electrically large apertures, MoM should be enhanced by fast algorithms such as FMM or AIM as mentioned above.
3. Wide band antennas (spiral, flares etc.) pose a great deal of challenge in terms of computational time to characterize these antennas over a broad band of frequencies. Techniques such as Asymptotic Waveform Evaluation (AWE) or Model Based Parameter Estimation (MBPE) should incorporated in antenna analysis codes to get the wide band frequency response with a small number of frequency computations. (C.J.Reddy *et al*, "Fast frequency response of cavity-backed aperture antennas using hybrid FEM/MoM technique in conjunction with model based parameter estimation," *Applied Computational Electromagnetic Society Journal,* Vol.13, pp.283-290, November 1998.)

—Comments on Antenna-Platform Interactions:

Modern day communications require complex, conformal, multifunctional antennas to be mounted on very large and complex platforms. In most cases, the platform itself can be analyzed using MoM technique. The conformal antenna such as a cavity-backed aperture antenna requires a volume-based technique, such as FEM. If the antenna and platform are analyzed together, the cavity requires a volume mesh and the platform requires a surface mesh. Due to the complexity associated with mutifunctional antennas, the cavity requires a fine mesh to represent the geometry and material details, and hence resulting in a large aperture mesh to be coupled with the platform surface mesh. This approach also requires that a new geometry and mesh is required if the antenna location needs to be changed. An innovative technique is being developed to decouple the antenna and platform, so they can be analyzed as separately. The cavity-backed antenna is analyzed using either FEM or Finite Difference (FD) methods. The resulting antenna fields are superimposed on MoM based surface meshes. This novel approach allows the reduction in the size of the matrix to be solved and also facilitates arbitrary placement of the antenna with no need for change in the geometry and mesh for the platform or the antenna.

❖ Response 2.21

—It is important to point out to the designers and users of antenna tools that for conducting structures – does not matter how complex it is – it is difficult to beat the efficiency and accuracy of an integral equation approach !
—Even with bulk dielectrics a surface integral equation in the frequency domain is more efficient than an FE based code.
—Also hybrid methods using both time and frequency domain informations simultaneously can generate results from DC to daylight on small platforms.

❖ Response 2.22

—The "map" seems mostly complete and valuable. However, the devil is in the details, such as the ways in which features can be combined and the resources needed to solve any particular problem.
—I.C.3. "Scalability" of the software would be very useful. That is, most or all features can be used on a reasonably good workstation. Using a faster computer with more memory improves execution time and increases the size of the problem that can be solved. But, it is desirable that everyone not be required to purchase the latest, greatest computer just to benefit from the tools.
—I.D. Time domain codes can be of great value for some applications.

❖ Response 2.23

—I agree with the general tone and content of the antenna-platform interaction software toolbox document. In fact, the underlying concepts and sentiment are basically what motivated our own development of the EIGER software suite. We saw the need to be able to address many of the analysis methods described in the document simultaneously, for advanced antenna systems and complex platforms. Many of these systems will require a complete self-consistent solution, rather than a piece-wise coupled solution. The tools that we are developing allow most of the aspects mentioned in the document to be applied simultaneously, if necessary.

❖ Response 2.24

—The preparation of the above document is a very appropriate and timely undertaking, as the need for accurate and efficient antenna design software is more than ever felt. The list of requirements for the Antenna Design Tools covers the major features desired by most antenna designers. The following additional features are suggested:

1. (Section I.A) The integration of antenna (element) design software and array design software into a unified package is very useful especially when inclusion of coupling effects is needed.
2. (Section I.B) Parametric Sweep as a function of various geometry and material parameters is fundamental to the design process and oftentimes helps narrow down the range of parameters for optimization. Sensitivity analysis is also important from a manufacturing point of view.
3. (Section I.B) Having dual or multiple engines for analyzing or designing a certain antenna gives the designer the flexibility over accuracy, speed, memory usage and the problem size

limit. In specific, the combination of a full-wave engine and an approximate analysis technique (e.g. based on network models, array factor, etc.) is highly desirable.

4. (Section I.B) The capability of full-wave treatment of finite large-scale and infinite periodic antenna arrays should also be addressed.

Section II of the document on Antenna Platform and Antenna-to-antenna Interactions is particularly well drafted. The development of this type of EM codes should be seriously encouraged.

❖ Response 2.25

—Looks good to me. I tend to favor exact methods for on aircraft antenna patterns, since there is little reason to question the results. Codes like **NEC-BSC** are used improperly more than not, and cannot deal with radiating structures in the near field of a platform, which is the norm & not the exception. The mind boggling increase of computer speed & power will likely continue, exceeding even Moore's Law. As this pattern unfolds, high frequency methods will become correspondingly less desirable. Efforts should be focused on usability, e.g., ridding every EM code from its dependence on external geometry generators like **I-DEAS**, inclusion of optimizers, etc. These enhancements will remain even after a thousandfold increase in computer speed and memory.

❖ Response 2.26

—I believe that the Road Map does an excellent job in presenting what is really critical to antenna modeling and analysis engineers and scientists. However, the GUI interfaces should be stressed further that they have been. Ease of use should be an important goal as well.

—As far as accepting different file formats is concerned, some formats should be specified, such as DXF, IGS, etc. Also, maybe some examples of software capable of model (mesh) generation, such as **I-DEAS**, **PATRAN**, **NASTRAN**, etc.

❖ Response 2.27

—<u>Comments on Antenna Design Tools:</u>

I would include

Matrix Boundary Conditions
Higher order boundary conditions
Higher order elements

Under item 6: Instead of Sommerfeld Integrals, I would say 'treatment of layered structures".

With respect to GUI, I would leave it out in the initial list. A GUI implies a commercial product and should not be considered under the same roof with the development tools.

One critic that I may make is a need for some specific goals. Give examples of some goals. That is, tools need to be able to handle
– Dynamic range of 60dB

– Should solve 100 wavelength problem sizes on a PC or some other platform
– List a few application problems which are now pressing and need solution
– Discuss the value of these tools; what will they allow us to do that is not possible before?

Appendix C: Raw Form of Part III of Survey Data

III. Please list by name and critique ACEM software you have developed or you are using. Suggest enhancements along the lines of II above. If software is of the "home-grown" variety, please supply a short description mentioning the type of computational engine they use and the kinds of antennas you design with them.
Please note: Each bullet (❖) represents one person.

❖ Response 3.1

—"Homegrown" codes are used to design and analyze reflector-based antennas.
—"Homegrown" codes are used in planar array designs.

❖ Response 3.2

—We are using, especially for validation, the **NEC** code. We found this to be very good for most cases.
—We are developing our own codes, especially for our own needs and our sponsors:

1. **NEWS** (Numerical Electromagnetic Wave Simulator). This is an FD-TD based code that we have developed to analyze radiation, scattering and penetration problems, especially for complex platforms (i.e., helicopters, airplanes, ground vehicles, etc.). The code is interfaced with other available software (especially **BRL-CAD** based) to automate the geometry (**MGED**), meshing (**ANASTASIA**) and **IMAGE** (geometry viewer) of the system. Various different post-processing software (**GLE, DRAW**, **TECPLOT, PLOTMTV**, etc.) are used to process and illustrate the data.
2. We are in the process of developing another software package, similar to **NEWS** but based on FEM. It also is intended to address radiation, scattering and penetration problems, especially related to complex platforms.

❖ Response 3.3

—No comments.

❖ Response 3.4

—One antenna software we have developed in our Center is **FISCRAD**, and Fast Illinois Solver Code for Radiation calculation. It can handle wires radiating in the presence of complex platforms such as an aircraft or ground vehicle. However, we do not have enough resource to push for a more matured development of this software. Our Center has to develop scattering codes, material scattering codes, as well as this code.

❖ Response 3.5

—John, I have not finished with this one. I am still trying to get input from the users as to what their opinions are. I will submit this sometimes early this week.

❖ Response 3.6

—Home Grown codes:

1. Multi-layer infinite array printed microstrip/dipole analysis code (developed at AFRL)
    1. Electric field integral equation – frequency domain
    2. Prode feed and proximity coupled line feed
    3. Dual and circularly polarized feed analysis
    4. MoM with entire domain and sub-domain PWS basis functions
    5. Conjugate gradient solver
    6. No GUI
2. Finite Element Radiation Model (FERM) (developed at MIT Lincoln Lab)
    1. Electric field integral equation – frequency domain
    2. Plate type MoM
    3. Delta gap sources
    4. Infinite and finite ground planes
    5. No dielectrics
    6. No GUI
3. PARANA
    1. 3D finite element frequency domain
    2. Infinite array periodic boundary conditions
    3. Multiple ports
    4. Accepts PATRAN and IDEAS geometry files
    5. No GUI

—Commercial:

1. **XP3**
    1. 3D finite element frequency domain
    2. Infinite array periodic boundary conditions
    3. Multiple ports
    4. Accepts PATRAN and IDEAS geometry formats
2. **Ensemble –** well known commercial MoM code

❖ Response 3.7

—I am a developer and user of the CARLOS code and its hybrid versions using FEM and asymptotic techniques. These codes already satisfy many of requirements outlined, but there is still much work to be done. Specifically, a “fast” solution approach is needed for large problems (i.e., platform integrated antennas) and new basis functions (namely, loop-star) are needed for low-frequency problems. The code is also rather difficult for the nonexpert to use and since it is not distributed commercially, user friendliness has always been a low priority.

❖ Response 3.8

—**ANSOFT-Ensemble**: Method of Moment solution to analyze and design multilayer microstrip antenna problems.

—Reflector code from University of Illinois, Champaign, IL: Developed by Professor S.W. Lee using PO/UTD to analyze and design various reflector antenna configurations.

❖ Response 3.9

—I have been heavily involved with the development of codes known as the Aircraft inter-Antenna Propagation with Graphics code (**AAPG 2000**), and Diffraction Over Virtual Aircraft (**DOVA**). These codes employ the Uniform Geometrical Theory of Diffraction (UTD) in conjunction with novel ray trace techniques to compute patterns and coupling effects for platform-mounted antennas. Unlike previous UTD codes based on canonical shapes, these codes employ a realistic platform representation in terms of triangular facets. The ray tracing involves selection of starting paths, followed by convergence to extremal paths via a "diffusion" algorithm. The implementation of the UTD within these codes includes both wedge and smooth-surface diffractive mechanisms. Inclusion of the latter is possible because the facet representation has been demonstrated to reliably support UTD treatments for smooth surfaces. The **AAPG 2000** code is used extensively at the DoD Joint Spectrum Center to assess the electromagnetic compatibility (EMC) of aircraft-mounted electronic systems. The **DOVA** code has not yet been completed.

Suggested Enhancements:

1. Hybridization of both of these codes is under investigation. This is an essential step, as noted earlier.
2. Platform material properties need to be included in these codes. An important but difficult problem derives from the fact that these codes should be able to predict shadow-region patterns and coupling in cases involving the creeping-ray mechanism. Even for a conducting surface coated with a single layer, or a simple impedance surface, no creeping-wave solution has been available for cases where the surface has general curvature in two directions. I proposed a solution at the APS/URSI meeting last summer, and am currently working towards implementation into AAPG 2000.

Our ray-trace scheme is oriented towards aircraft. This algorithm places no limits on the number of times a diffractive mechanism is allowed to occur, but each path involves at most one reflection. The inclusion of further reflections would help to make these codes more applicable to a shipboard environment.

❖ Response 3.10

—I have assisted in the development of post-processing tools for **EIGER**, an multi-purpose object-oriented computational software tool being developed jointly by Lawrence Livermore National Laboratories, Sandia Laboratories, and the University of Houston. I believe that **EIGER** is a leading-edge ACEM tool that shows the future for software development in this area One of its main characteristics is that it is based on object-oriented FORTRAN 90. This object-oriented approach allows different types of basis functions to be modeled in a unified fashion. In this approach the incorporation of different types of Green's functions into the code to treat different types of canonical problems becomes much more direct, avoiding the necessity of writing entirely new codes to treat different geometries. New types of basis functions can also be directly added to the code without re-writing the entire code. This is because the object-oriented approach allows for a unified treatment of reactions between basis functions using various Green's functions. For example, modeling the reactions between basis functions in diverse problems, such as triangular roof-top functions on a flat plate of tetrahedral elements inside a volume, are thus done using the same code. If new basis functions are added in the future, a new type of basis function class is simply added. The object-oriented approach also allows for post-processing parts to be added to the code with minimum effort. This allows for the calculation of figures of merit such as antenna gain, efficiency, etc., to be added to the code in a direct way. This code therefore provides maximum versatility and expandability, which is one of the most important requirements for multi-platform ACEM software.

—In our group we also are end users of the code **IE3D** by Zeeland software. This is a very versatile MoM code for analyzing either antennas in free space or in a layered media. This software tool have a very good GUI, which is one of its strong points.

—We use ACEM codes to design microstrip antennas, and antenna for wireless communications.

❖ Response 3.11

—NRL Multi-layer **FDTD3D**: 3D FDTD total field formulation with YEE-like material absorbing boundary conditions and lossy multi-layer media.

—REMCOM **XFDTD**: 3D FDTD code. NRL has modified the 1995 source code to handle multiple feeds, 128 materials, and to generate admittance matrix data for antenna array mutual coupling for post-processing active array scan VSWR. The more recent versions of XFDTD probably have greatly expanded capabilities.

—NRL FDTDGEOM: Grid generation software for NRL **FDTD3D** and **XFDTD**. Outputs geometry files to be viewed in AVS and MCAD as well.

—**CARLOS**: MoM-FEM 3D software.

—**ESP4**: OSU MOM 3D software with plates and wires.

❖ Response 3.12

—No comments

❖ Response 3.13

—Utilize commercial software such as NEC, HFSS, ENSEMBLE.

❖ Response 3.14

—NO comments.

❖ Response 3.15

—Matis, Inc. has developed:

1. Propagation Path Finder (**PPF**) – the geometry engine of AAPG2000, currently in use at Joint Spectrum Center (via IITRI) for EMI/EMC predictions.
2. Diffraction Over Virtual Airframe (**DOVA**) – a code for predicting the "net" patterns of airborne antennas. The code is designed to perform required calculations on platforms modeled by realistic CAD-based models. It has an extensive user-friendly GUI and a post-processing utility for viewing and printing the results. It also includes visualization tools for viewing in real-time the platform, propagation paths, etc.
3. **CDOVA** – a code for predicting coupling/isolation between pairs of airborne antennas. It also runs on realistic CAD-based models, has a GUI, a visualization, and a post-processing subsystems.

Both, **DOVA** and **CDOVA**, are HF codes. Both run in nearly real-time on a low-end work-station. They are real-time when run on a multi-processor machine or a network of computers. Currently, both codes accept six classes of basic antennas modeled with pattern factors. More information about **DOVA** can be found at
www.matis.net
One important enhancement would be to link the **DOVA** and **CDOVA** with an exact code(s) with capabilities to model large antennas. Provisions for such enhancements are built into **DOVA** and **CDOVA**.
Another important enhancement is to add capabilities for running **DOVA** and **CDOVA** on CAD models representing platform surfaces by NURBS (Non-Uniform Rational B-splines). The currently used CAD models must be faceted. For several reasons simple format conversion from NURBS representation to faceted, while possible, is not always desirable nor is the most efficient way to approach this problem.

❖ Response 3.16

—NRL is using several packages in addition to ones we have developed to design Ultra-Wide-Band phased array antennas for a number of applications.
—We are using FD-TD codes both home grown and commercial (XFDTD).
—Also FEM and MoM codes: Carlos 3D, etc.

❖ Response 3.17

—I have developed **PCAAD 4.0**, the fourth version of a Windows-based package for general antenna analysis and design (wires, arrays, microstrip antennas, horns, reflectors, etc). This package uses simple cavity-type models and aperture integrations, and is relatively inexpensive. I have also developed about a dozen specialized codes for the full-wave analysis of microstrip antennas and phased arrays. I occasionally use **Ensemble**, and my students occasionally use **Momentum**.

❖ Response 3.18

—We have developed an in-house computational EM code named **CARLOS** which is described in the April 1993 AP Magazine on page 69. This code was developed primarily as a RCS analysis tool, but is also applied extensively within Boeing for antenna modeling. It is a surface integral equation method-of-moments based code using triangular or quadrilateral patches for 3D geometries, although it can also model body-of-revolution (BOR), wire, and 2D geometries. The code has also been coupled with a finite element code (**CAFE**) forming a hybrid MM/FEM capability for modeling interior inhomogeneous or anisotropic materials. The code has been successfully used to model a variety of antennas, including spiral, patch, flared notch, Vivaldi, monopole, and slot type.

❖ Response 3.19

—At Applied EM Inc. we are developing **ASET** – Antenna and Scattering Evaluation Tools, state-of-the-art antenna analysis code. By the use of muLti-resolution elements and smart matrix solution algorithms, the memory and CPU times requirements are reduced. Platform interactions with the antenna are included in the analysis to characterize the antenna at multiple locations on the platform. Decoupling of antenna analysis and platform analysis is achieved through accurate and rigorous analysis. Despite of the large gains in terms of memory and CPU time, the real life platforms are electrically very large in size and require parallel computers to solve the problem in reasonable time. Fast techniques such as FMM and AIM will make this software a viable tool that can be used on a desktop PC for the analysis and optimization of the antennas on large platforms. **ASET** software is based on MoM with multiresolutional elements and fast algorithms. Cavity-backed antennas are analyzed using FEM/MoM based technique. **ASET** software is being successfully used to characterize antennas on aircrafts, automobiles and ships.

❖ Response 3.20

—We have developed **WIPLD** which is a commercially available software capable of solving real life problems in reasonable time on a PC. It can handle most of the problems cited in the document. However for FSS a floquet type expansion can be more advantageous. However for a finite sized composite structure **WIPLD** is the only commercially available code at a reasonable price available to any interested researchers with modest means.

❖ Response 3.21

—PCAAD - this is a relatively simple analysis tool developed by David Pozar, Antenna Design Associates. It is easy to use on a PC and provides good starting point information for antenna design or for more extensive analysis. However, it is limited to the particular cases that it was designed to analyze.

—"Homegrown" MoM codes for analysis of infinite arrays of wideband Vivaldi tapered slot antennas. Used on medium level workstations. Lack good user interface and thorough documentation. Only useful for the canonical geometries for which Green's functions have been implemented. There is need for better codes to treat infinite and finite arrays of complicated elements (dielectrics, printed and machined metal parts, lossy and/or anisotropic materials).

❖ Response 3.22

—The **EIGER** software suite is a general-purpose hybrid FEM/MoM framework. The tools use both higher order geometry and basis functions. The MoM features can incorporate Green's function treatments for multi-layered materials and periodic structures (as well as combinations of the two). The tools also allow a variety of boundary conditions ranging from PEC and PMC to general materials, apertures and impedance loaded surfaces. General symmetries are also available for reflection and discrete rotational geometries. Different combinations of these features can be applied simultaneously to different portions of a complex problem.

—The list of antennas recently designed with this tool suite include (but aren't limited to) the following:

- Broad-band wire radiators
- Microstrip patches
- Spirals (equiangular, archimedian, and sinuous type) both planar and non-planar
- Broad-band horns
- Reduced surface wave antennas
- A variety of phased array and FSS geometries

—Additional information can be found at the following Web address beginning May 12, 2000: www-cce.llnl.gov

❖ Response 3.23

—**PiCASSO** is an antenna design software developed by EMAG Technologies, Inc. under a SBIR program funded by Army during 1996-99. It is meant for the analysis, design and optimization of printed antennas and arrays. Its main engine is based on the method of moments using a mixed potential integral equation formulation. It can handle an unlimited number of substrate layers and trace planes or ground planes. It is also equipped with a sparse moment method solver that enables the user to solve large-scale problems with more than 20,000 unknowns.

In addition to the full-wave engine, **PiCASSO** also has a model-based network engine. It can generate network models from full-wave simulation data and use them in a multi-port network analysis. The coupling effects among the array elements are taken into account through full-wave-based coupling models. **PiCASSO** also offers pattern synthesis capability through its genetic algorithm optimization engine.

Many of the features suggested in Part II above have already been implemented in **PiCASSO**, e.g. multi-variable parametric sweep, dual full-wave/network engine, etc. Under DARPA's RECAP program, the **PiCASSO** foundation is currently being enhanced with new features including a finite element engine for handling of MEMS structures and a periodic moment method engine for frequency selective surfaces and photonic bandgap structures. Under CHSSI program, a parallel version of **PiCASSO** and parallel versions of the subsequent finite element and periodic engines will be developed.

In the future, additional simulation engines including a time domain simulator will be added to **PiCASSO**.

❖ Response 3.24

—While not ACEM codes, I use **NEC** and **WIPL** exclusively. The one reason to use NEC is its ability to exploit rotational symmetry—body of revolution that permits asymmetrical excitations—very powerful indeed.

❖ Response 3.25

—**NEC** – Excellent MoM code for wire antennas. Patch capability is very limited and non-effective. Really like its allowance for symmetric and non-symmetric portions in a single model, as well as its rotational symmetry. Runs in both single and double precision modes. Needs a really good GUI (even better than what comes with **GNEC**).

—**NEWAIR** – Based on GTD/UTD. Antennas handled are limited to monopoles and slots attached to aircraft fuselage. Does not compute mutual coupling between antennas, antenna parameters, or currents on antennas or mounting structure. Does not handle wires, and does not have a graphical display for Windows environment.

—**NECBSC** – Based on GTD/UTD. Still in a beta-mode, and is being updated continuously. Antennas handled are limited to dipoles, monopoles (limited success), circular and rectangular loops, and slots. Doesn't compute mutual coupling between antennas, antenna parameters, or currents on antennas or mounting structure. Wire modeling has just been added. Has a graphical display/interface for Windows environment, which is being continuously updated.

—**WIPL-D** – Excellent MoM code for both wire and plate antennas and structures. Very good code with good pre- and post-processing interfaces. Needs a double precision version. Allows for multiple material definitions. Variables can be defined using symbols, thus simplifying changing the values of like variables. **WIPL-D** allows for PEC, PMC, symmetry, and anti-symmetry options, among others. Double precision mode is not currently available. Some aspects of the code need improvement. Currently, if a source lies in a region of symmetry, the source is automatically transferred with that region. This is not a desirable situation, since source magnitude and phase values could vary considerably from one source to another. However, that same scenario is not true for a load in a region of symmetry, which normally is desired to be transferred with the region of symmetry. Also, there are options in the Windows version of the code that are currently not fully operational.

❖ Response 3.26

—Some of the currently used codes for antennas:

TRIMOM: moment method code using the Rao-Wilton basis for antenna and scattering.

TRIMOM-FMM: moment method code with fast multipole method.

BRICK/XBRICK: finite element-boundary integral code for conformal antenna analysis using bricks for modeling the volume and squares for the surface.

FEMA-PRISM: similar FEM-BI code to **BRICK**. It uses prisms for the volume and triangles for the surface.

MR_TETRA: FEM-BI code for antennas. Use tetras for volume and triangles for surface. Also it incorporates multiresolution elements which are crucial for input impedance calculations.

ARRAY_TETRA code for antennas. Similar to **MR_TETRA** except for periodic volumes and surfaces. Both, **MR_TETRA** and **ARRAY_TETRA** incorporate fast algorithms.

FSS-PRISM and **FSDA-PRISM**: Extremely fast O(N) CPU and memory codes for Frequency selective surface and array modeling on infinite and finite substrates.

SWITCH-FMM: general purpose scattering and antenna analysis code based on Northrop's **SWITCH** code. It includes fast multipole method and FEM. Was developed with Northrop-Grumman.

CADRISA: General purpose scattering and antenna analysis code using the Adaptive Integral Method(AIM).Code can handle various material and impedance regions/surfaces as well as general junction. This is a very new code.

Appendix D: Raw Form of Part IV of Survey Data

IV. Please give us your thoughts on what the principal thrust of ACEM research should be for the next three to five years.
Please note: Each bullet (❖) represents one person.

❖ Response 4.1

—Antenna-platform and antenna-to-antenna interaction tools are needed.

❖ Response 4.2

—I also very strongly believe that Hybrid Methods will be the ones that will solve electrically large structures, the same way as it was stated in the road map. That is, treat the antenna and its vicinity with a low frequency method (such as FEM, FDTD, MoM, etc.) and the remaining large part of the structure using a high-frequency method (such as PO, PTD, GTD, etc.). Otherwise it will be a long time before larger structures are treated accurately just with the limitations of each one of the individuals methods has.
—It seems that the main objectives so far are related to software (code) development. This basically parallels what the EMCC did/doing for scattering; nothing really "earth shaking".
—I believe that the ACEM should also play an advocacy role in innovation and advancement of antenna technology. If we do not advance and innovate, we will not have anything to apply the developed software.
—Wireless communication is in need of innovation of antenna technology (for example, smart antennas). Are there similar innovations and advancements?

❖ Response 4.3

— I can not speak with authority here, but here are my thoughts. In all scientific and engineering fields, there are a great number of analysis codes. However, there is a lack of good design tools. A design code and analysis code are two very different beasts. Design codes often employ a mix of empiricism and theory. Rarely are the exact equations solved. However, good analysis codes are also needed since in the end the design tool must be verified. Sometimes you get stuck using the design tool and have to use an analysis tool to figure out why the design tool is failing. But design is an iterative an interactive process. You need to go back and forth between the two types of tools easily.

❖ Response 4.4

—Hybrid codes and fast methods for treatment of structures combining large and small parts.

❖ Response 4.5

—ACEM should be broadband, memory and CPU efficient, and be able to handle a large amount of details.

❖ Response 4.6

1. Fast Solvers
2. Improved geometry/meshing tools or additions to existing CAD programs—also include data display
3. Exact methods to treat large finite arrays embedded in materials
4. Improve impedance predictions of various antenna types
5. Isolation between apertures
6. Optimizers
7. Design methodology….code usage is not currently very cost effective.

❖ Response 4.7

—See Section II.

❖ Response 4.8

—Installed antenna performance is inherently a multi-scale problem. Research should be directed toward numerical methods tailored to this class of problems.

❖ Response 4.9

—With so many powerful analysis codes available, I suggest to start the development of synthesis codes. It will allow a non-antenna engineer to design antennas with a set of given system requirements. The current analysis codes still require antenna experts to effectively use them. Software code similar to Genetic Algorithm should be the direction to go.

❖ Response 4.10

—Well, of course, methods like fast multipole and FE will, and should, get a lot of attention. I believe, however, that the HF techniques still have an important role and some effort should be devoted to them. Extending these techniques to work in environments comprised of various materials will, I am sure, not be the "principal thrust of ACEM research," but to me this seems an important and challenging problem.

❖ Response 4.11

—I think it would be a good idea for antenna code development to continue simultaneously in the areas of MoM, FEM, and FDTD. In each case, the incorporation of a user-friendly GUI is essential. The availability of several different types of codes, using different types of computational engines, will give users a choice of approach that is the most appropriate for their particular problem. Having a suite of codes available is also important for verification purposes. An example of this is the company Zeeland Software, which markets two different products, one based on Mom (**IE3D**) and one based on FDTD (**Fidelity**).

❖ Response 4.12

—In general we believe the Full-Wave solutions are the only calculations that can be relied upon to produce accurate antenna parameter results. To get to the next order of antenna problem size, the frequency-domain Nystrom formulation for integral equations (Wadzura, HRL) seems to be one of the more promising solutions when combined with a fast solver such as FMM or AIM. Extensive research into singularity extraction has been and will continue to be priority for large problem solution convergence. Among time-domain formulations, FDTD is more of a brute force technique although modified grid techniques will make it more efficient. Finite-volume and characteristic-based equation techniques (Shang, WPAFB) appear to have greater potential for efficient solutions.

❖ Response 4.13

—It is difficult to give the same advice to different research groups. Actually, everybody must improve his own method, but with the same goals: to increase the flexibility, accuracy, and efficiency. The general trend is hybridization. However, it is not so easy. For example, the MoM specialists are far away to be specialists for high frequency technique, and vice versa. One possible solution is to join these specialists. Another possibility is to make independent programs (e.g. one MoM, and another high frequency) that are able to communicate. If the language of communication is standardized, different hybridization can be made. (For example, the hybridization is always performed through boundary surfaces. In my opinion optimal elements for description of boundary surfaces are RWG triangles and **WIPL** quads. They can be used as standard elements for communication.)

❖ Response 4.14

—Need to develop a user friendly Finite Time/Frequency Difference codes for parallel architectures.

❖ Response 4.15

—No comments.

❖ Response 4.16

—Develop hybrid antenna codes capable of running on CAD models, faceted and NURBS. Issues related to accuracy should be also investigated. This is very much in agreement with the discussion in part B, section II.

—Investigate issues concerning use of CAD models in ACEM codes (geometry representation and repair, extraction of high-order geometric data, meshing, etc.)

❖ Response 4.17

—Its still the same, ability to handle very large and extremely complex material embedded antennas.

—Antenna system size is on the order of 30 by 30 by 2 wavelengths.

❖ Response 4.18

—This is hard to answer. The market for antenna CAD software is relatively small, but commercially available software is beginning to be produced with increasing capabilities, and there seems to be enough demand from users to support a number of vendors. In this sense, then, the marketplace will likely produce the best product, in terms of ease of use, availability, and features – things that are not likely to be enhanced by government or organizational meddling.

—On the other hand, research money could be provided by the government to support R&D into improved algorithms and more basic types of investigations. After all, the present EM software industry largely evolved from work done in academia, as supported by NSF and DoD funding.

❖ Response 4.19

—I would say the development of tools for predicting the antenna/platform interaction effects based upon some sort of hybrid approach.

❖ Response 4.20

—ACEM research should be focused on development of fast algorithms for antenna analysis. These include but not limited to FMM and AIM techniques. Frequency extrapolation techniques such as AWE and MBPE are essential to be incorporated into the ACEM codes to characterize the antennas over a wide frequency range. As the platforms play an important role in the performance of the antenna, development and enhancement of powerful tools to optimize the location and performance of the antenna on a platform. This tool should be fast and efficient to be able to work on a desktop PC.

—CEM community in general and ACEM community in particular lack dedicated mesh generation tools geared towards ACEM analysis tools. Currently geometrical and meshing packages are borrowed from other disciplines (Computational Fluid Dynamics, Computational Structures etc.), to be used with CEM codes. Development of a geometry and meshing tool for ACEM codes will enhance the power of these codes to a great extent. It will be worthwhile to either develop or modify existing tools to suit the needs of ACEM codes.

❖ Response 4.21

—The problem is not so much research as information dissemination with certain degree of integrity. It is important to provide the pertinent information succinctly and accurately without any veils of mystery. The information in the consortium should be made open to researchers rather than serving vested interests of particular groups.

❖ Response 4.22

—Antenna arrays of complicated elements, especially finite arrays containing 100 - 2500 elements.

❖ Response 4.23

—No comments.

❖ Response 4.24

—As more sophisticated antenna systems gain practical applications, there will be a need for more complex antenna design tools. One example is reconfigurable aperture antenna arrays, which span different technologies and pose various modeling needs. The principal thrust of ACEM research for the next three to five years should be hybrid modeling tools that combine different techniques to treat complex antenna structures. Such techniques are needed for both antenna design and study of antenna-platform and antenna-to-antenna interactions. Hybrid moment method/network, FEM/network and MoM/FEM codes will be useful for analysis and design of antenna elements and arrays, while hybrid MoM/HF and FEM/HF codes will address the study of antenna interactions.

—Another research area demanding more attention is the modeling and design of antennas based on complex materials. Examples are lens-based antennas, chiral antennas and antennas with magnetic, biased, ferroelectric, anisotropic substrates, etc. Developing general-purpose codes for the analysis and design of such antennas will be pivotal for the advancement of next generation antenna systems.

❖ Response 4.25

—Fast solvers, optimization, efficient and integral geometry generation.

❖ Response 4.26

—Full hybridization.
—Optimization.
—Fast solvers.
—GUI's.
—Geometry generation.
—Automatic meshing.
—Post processing.

❖ Response 4.27

—Benchmark problems.
—Dual use applications (Cars, wireless telephony).
—Hybrid methods development.
—Time Domain.
—Broadband Antennas.
—Design (perhaps the most important effort) with specific goals in mind.

Appendix E: Raw Form of Part V of Survey Data

V. What areas of your business/research/technology does ACEM impact and to what degree? Please help us make a case for you. The EMCC will only make suggestions to the Government. It will not be involved on how contracts will be given out or in their management. The more information you provide, the better for all concerned.
Please note: Each bullet (❖) represents one person.

❖ Response 5.1

—The Air Force has wide needs for antenna design tools.

❖ Response 5.2

—There are many centers of excellence of antenna technology. The government should look very carefully which are these centers of excellence that actually do deliver and not put on the efforts on some very generic research efforts that ultimately are very academic and have no practical use.

❖ Response 5.3

—My job is to look at ways of integrating electromagnetic requirements into the aircraft design process with a view towards optimization. Immediately everyone thinks of stealth, which is what I am currently working on. However, the people I work with are involved with an ISR platform (Intelligence, Surveillance, Reconaissance), which is basically a big flying antenna. There are a whole host of antenna-platform integration issues given that the antenna and the aircraft are really one structure. Sometime within the next year I hope to begin looking at antenna integration on air vehicles. For me and my organization, ACEM would impact mostly the front end of the design process (conceptual design). Of course we do some detailed work as well such as wing and fuselage design, which could be influenced by antenna requirements at a more detailed level.

❖ Response 5.4

—Education.

❖ Response 5.5

—Our business deals in Countermeasures (ECM and ESM) and SIGINT. Our systems cover frequencies from MF to 96 GHz. We have a need for very broadband antennas for the countermeasure systems and high gain, efficient antennas with moderate instantaneous bandwidth tunable over a wide operational bandwidth for the SIGINT systems. Many of our ESM systems do precision DF and hence require broadband, phase stable antennas with predictable phase slopes. Our DF systems oftentimes require expensive calibration, where large portions of a platform needs to be constructed with apertures installed to make the measurements. Of all our business areas, the DF group has the greatest need for good modeling tools that can accurately predict installed performance in terms of phase, polarization, platform effects, mutual coupling, etc. Other business areas desire antenna designs and better performance. The need for ultra accuracy is not as great there since their major concern is interaction or mutual coupling between systems.

—Sanders has three antenna design departments with emphasis in DF, broadband CM apertures for aircraft, and Low Observable Apertures for all platforms. The DF group covers frequencies from MF to K-band. The CM group concentrates on UHF, L-, S-, C-, X-, Ku-, & Ka-band antennas. The LO group concentrates on all bands with emphasis on array and aperture antennas. This group designs apertures that cover VHF through W-band for installation on aircraft, ships, submarines, and ground vehicles. The number of antenna engineers in the company exceeds 100 people.

—Therefore, antennas are a vital part of our business. They form the eyes to many of our systems.

❖ Response 5.6

—<u>RF Sensor Technology:</u>

1. Foliage Penetration Radar(SAR, GMTI, EW): utilizes low frequency (VHF-UHF) wide bandwidth scanning arrays, where complex 3D elements are required to achieve the band coverage. The array edge effects are substantial, as are the platform interactions. Full wave analysis of platform effects is computationally intensive, and use of diffraction techniques is questionable.
2. Large phased arrays for surveillance and tracking, airborne SATCOM.
3. Small conformal arrays on platforms for GPS.

❖ Response 5.7

—Advances in ACEM are essential for design of the next generation of aerospace vehicles. Antennas are simultaneously becoming more complex and more mission-critical. In particular, development of effective and survivable unmanned vehicles will require better antenna design and analysis software than is currently available.

❖ Response 5.8

—Antenna design, development, and research for spacecraft technology will be impacted by ACEM.

❖ Response 5.9

—The IIT Research Institute staffs the DoD Joint Spectrum Center (JSC), which is tasked to provide guidance throughout the US DoD with regard to issues of EMC and electromagnetic interference (EMI). Our requirement is for computationally efficient, user-oriented, ACEM software that can support analyses of EMC/EMI in aircraft, shipboard, and other environments. HF codes, such as our AAPG and the Ohio State University's Basic Scattering Code, have been used extensively because they are fast and provide a level of accuracy that is satisfactory for our purposes. Antenna modeling is frequently performed, and the NEC model has received particularly wide use. The JSC has expended considerable internal resources in code development, and has procured a wide array of externally developed codes. The goal has been to provide products that meet the needs of the IITRI/JSC internal user community, which is, by and large, comprised of people who are not ACEM experts.

❖ Response 5.10

—From a research point of view, ACEM is very important for advancing new technology. Having good computational tools available will free researchers from the burden of spending an inordinate amount of time developing in-house programs and analysis techniques in order to analyze new antennas that are proposed. Having good ACEM tools will allow researchers to devote more of their time to designing new antennas and testing their ideas for novel antenna designs with "virtual experiments", rather than developing specialized analysis tools or performing costly measurements. This translates directly into increased productivity for achieving revolutionary antenna designs in areas such as wireless communications, where the antenna are often sufficiently complex that ACEM tools are mandatory.

❖ Response 5.11

—ACEM has provided us the tool to demonstrate wideband antenna technologies for shipboard applications (AMRF).

❖ Response 5.12

—No comments.

❖ Response 5.13

—Efficient, accurate and cost effective way to design antenna!

❖ Response 5.14

—No comments.

❖ Response 5.15

—The main areas of business at Matis, Inc. are research and development of new fast and accurate methods for predicting performance of antennas mounted on complex platforms. This is a critical technology for DoD and civilian agencies and industries.

❖ Response 5.16

—We are heavily involved in shipboard, aircraft, and space phased array design and application.

❖ Response 5.17

—I would say that the software I have developed has been an outgrowth of basic research that was supported by federal funds. Such funding has all but stopped, so it is likely that progress in computational EM will also level off, while the problems that need to be considered from a CEM viewpoint are increasing in number and difficulty.

❖ Response 5.18

—Aircraft and missiles have a variety of antennas of different types and for different purposes, and it is important to predict the installed antenna performance and coupling with other antennas on the platform.

❖ Response 5.19

1. Applied EM Inc. is poised to launch a commercial antenna development tool and greatly depends on the development of fast algorithms for antenna analysis. These techniques will make our software work with less memory and CPU time and hence speeding up the design cycle.
2. It is our experience that powerful analytical techniques have to be packaged with a user friendly graphical user interface (GUI) to be productive for an antenna designer. Development of sophisticated GUI with pre and post processing tools is critical for the success of our antenna analysis software tools.
3. An integrated geometry and meshing package tailored for antenna analysis tools is also crucial for the success of our software tools.

❖ Response 5.20

—EMCC has not so far made a case to the society to exemplify that antennas are an important integral part of life. Without it no system is going to work well. Demonstrate to the appropriate powers that an improvement of the design in an antenna can reduce the system power requirements and thereby making the devices more compact and efficient than ever before.

❖ Response 5.21

—No comments.

❖ Response 5.22

—No comments.

❖ Response 5.23

—EMAG Technologies is involved in the development of both software and hardware for antenna systems. On the software side, we develop electromagnetic CAD tools based on advanced modeling techniques with user friendly interfaces. On the hardware side, we are in-

volved with the design and prototyping of novel antennas for various communication and sensing applications. Examples include integrated multifunction antennas for automotive communication and navigation, wireless and millimeter wave sensor applications.
As antenna designers, we desperately need more powerful antenna CAD tools to reduce the costly design cycles. For example, in the design of antennas for automotive applications, an understanding of the interaction of the antenna with the vehicle environment is critical. We have to develop in-house codes for such purposes. As antenna software developers, we are constantly trying to bring some of these codes to commercial use. The major challenges on the way of commercial development include general-purpose (and not project-oriented) engines, easy-to-use interface and rigorous testing.

❖ Response 5.24

—No comments.

❖ Response 5.25

—ACEM is a critical aspect of how we are and will be doing business. We are asked to solve problems of antennas on aircraft, helicopters, and other specialized structures. We perform both measurements and computational models. But, when it comes to performing "what if" studies, as well as concept developments, physical models and measurements become almost obsolete due to the exponentially increased time and expense needed to perform such measurements. On the other hand, computational modeling serves as an excellent quick, accurate, and relatively inexpensive way to perform the task at hand.
—Having the proper ACEM tool(s) at hand is critical to the success of our mission. Not having such tools forces us to use inefficient modeling techniques, which would impact our productivity and the accuracy of our results. Also, we are sometimes forced to model only a portion of the model at hand, thus never realizing the effect of the full structure on the performance of the antenna(s) at hand.

❖ Response 5.26

—Previous and traditional efforts in CEM and ACEM have been driven by specific project applications and needs. Also, antenna design was primarily done experimentally with little or no simulation in the loop.
Currently there are lots of software for narrow band antennas, but no software available (except for home grown Univ. codes) are available for designing future multifunction antennas. The lack of support for FSS design tools is a more puzzling issue. FSS have been developed since the 1970s. However, to this point, the more powerful FSS analysis tools have only been designed as an outcome of antenna needs. This is an example that may be interpreted as lack of interest. However, when compared to existing/established efforts in CFD and Computational Mechanics, the lack for similar efforts/interest in CEM and ACEM is puzzling. A possible explanation is that DoD companies have had considerable internal research activities that to a great degree were focused on the support of projects. However, today's reality is very different:
1. only a few major procurement projects are now in the works.

2. These few procurement projects require high tech efforts and integration which is no longer available in a single company.
3. The usual cycle of 10 years or so to develop a new platform has been replaced by a short term 3-year plan. In this case, success depends on the availability of software design tools which will shorten the test and evaluation as well as implementation cycle.
4. The maintenance of large research groups with specialized expertise within the large organizations is a thing of the past.
5. We must now rely on multidisciplinary teams put together for a short period of time for delivering a specific product or platform. The availability of general purpose design tools with an integrated approach to design is the most likely future direction. In many cases, these tools must be used by engineers from other disciplines. Thus, design loops will play a major role and must integrate different criteria from different disciplines.

All this, makes the need for a concentrated government effort for CEM and ACEM very timely and crucial. Europe's commitment to such design tools is perhaps another example that we should follow. CATIA today is used throughout our industry. It is a French package that has the reliability and quality not offered by American gridding packages. The reason is mostly due to funding consistency and not to any technical advance contained in CATIA and which does not exist in the comparative American gridders.

Some other arguments:
- Antenna coupling to electronic systems is a new issue that must be addressed today
- Multifunctional antennas makes antenna design a more complex process.

Appendix F: Raw Form of Part V of Survey Data

VI. Finally, please suggest appropriate funding agencies for this effort.

Please note: Each bullet (❖) represents one person.

❖ Response 6.1

—Air Force Office of Scientific Research.

❖ Response 6.2

1. DoD
   a. Army (ARO, etc.)
   b. Navy (ONR, NAWC, NSWC, etc.)
   c. Air Force (AFOSR, etc.)
2. DARPA
3. NASA
4. NSF
5. Industry

❖ Response 6.3

—No comments.

❖ Response 6.4

—No comments.

❖ Response 6.5

—I think DOD and DARPA should fund this kind of work.

❖ Response 6.6

—No comments.

❖ Response 6.7

AFRL/AFOSR
NRL/ONR/NAWC
ARL
DARPA (SPO?)

❖ Response 6.8

—NASA

❖ Response 6.9

—No comments.

❖ Response 6.10

—ONR or NRL might be good prospects, because they often face the design of multiple antennas in complex shipboard environments, pushing the need for advanced ACEM tools to the limit.

❖ Response 6.11

—ONR, NAVSEA, NAVAIR, DARPA.

❖ Response 6.12

—No comments.

❖ Response 6.13

—No comments.

❖ Response 6.14

—(Alphabetically) AFOSR, ARL, DARPA, NASA, NSF, ONR

❖ Response 6.15

—No comments.

❖ Response 6.16

—No comments.

❖ Response 6.17

—No comments.

❖ Response 6.18

—DoD – Army, Navy, Airforce, Darpa
—NASA

—NSF (they have research center for mesh generation geared towards CFD and Structures)

❖ Response 6.19

—You need to form a group who will present the case to the politicians. Now research is done in congress and it is no longer being done in an university!

❖ Response 6.20

—No comments.

❖ Response 6.21

—Because of the high-risk R&D involved in ACEM, the Government should be and will remain the principal funding source. All branches of DoD are somehow involved with ACEM, and DARPA can be a good source of funding due to the advanced and exploratory nature of the effort.

❖ Response 6.22

—No comments.

❖ Response 6.23

—Suggestion of appropriate funding agencies is probably irrelevant. AFOSR and ONR will never be interested in putting in real world enhancements because they are not aware of the shortcomings of available codes. The reason for this is that they neither use such codes, nor do they take inputs from users. Useful developments can and will only come about as the result of a demand by users, and providing feedback directly to the developers.

❖ Response 6.24

—Navy, Army, Air Force, Department of Energy, Departments of Transportation, Air Lines Industry, Automotive Industry, and National Laboratories.

❖ Response 6.25

—Get several PMAs to support and commit a 3 year funding for the ACEM.

Appendix G: DoD High-Performance Computing Centers

In this appendix, we present the views of Mr. Ron Chase (rchase@arl.army.mil), current Chair of the EMCC, on antenna software and the DoD HPC environment.

"It seems appropriate in a document involving future directions in antenna analysis and design software to make brief mention of the computational environment and resources that affect analysis performance, and software development. The decades of the 80's & 90's have seen remarkable advances in computational hardware and infrastructure. Single processor scalar machines were greatly outperformed by the vector supercomputers of the 80's. Software developed initially for scalar architectures was ported to the vector supercomputers with minimal developer intervention. Smart compilers were able to provide code computation speedups in single digits simply by unfolding loops and efficiently filling vector registers. But the path to code computation speedups that would only be limited by the number of processors available to the user lay with the parallel machine architectures of the 90's and beyond. Unfortunately, there is no simple way in general to transition code developed for scalar machines to the parallel machines with any modicum of the capability promised by the architecture. The code must be rewritten from the beginning to "distribute" the computation of the problem among the available processors and to be consistent with the constraints of the architecture supporting the processors (memory architecture, for example). The developer also needs to learn a new programming "language" to provide for communication between the distributed pieces of his problem, and assure that various partial results are available in the proper sequence. The enormous overhead required to efficiently use the parallel machines has greatly reduced the porting of existing analysis codes to these machines.

Since High Performance Computing (HPC) historically has played a major role in the ability of the United States to develop and deploy superior weapons, and warfighting capabilities, the DoD proposed and developed the HPC Modernization Program, circa 1992, to integrate HPC into all aspects of Defense related research and development. Today, the HPC Modernization Office (MO) oversees the implementation of this computing initiative in three major areas. The HPC Centers acquire and provide the hardware infrastructure, the most up-to-date high performance machines, to a user base that exceeds five thousand scientists and engineers located at more than a hundred DoD laboratories, test centers, contractor and academic sites. To extend this hardware resource effectively to their user base, the HPCMO supports the continual improvement and expansion of the Defense Research Engineering Network. The HPCMO also manages the Common HPC Software Support Initiative (CHSSI) which is focused on developing scalable application supporting software to exploit the HPC assets. In addition to these three initiatives, the HPCMO manages the Program Environment and Training (PET) program that provides scientific and computational expertise to assist the HPC users in developing and porting application programs to the HPC machines.

The trend in hardware platform development is pushing toward "parallel" type architectures. The PC is now available in "server" versions with up to eight processors per system. Commercial EM codes such as Ansoft's HFSS can take limited advantage of additional processors in these systems. Multiple PC platforms integrated into Bewolf clusters are appearing in many university and industry settings. In addition, the use of specialized networking software often enables PCs in separate offices to function as an integrated multiprocessor system.

The development of future software and/or the enhancement of existing software will have to contend with the implications of the existing computational environments and infrastructure. A program that requires DoD support for software development will need to demonstrate a detailed knowledge of the HPC architectures and resources, and project the attendant increase in capabilities that accrue from the use of such platforms. On a final note, the parallel machine architectures are a valuable resource for the solution of large, real world, complex problems, but they are not a complete answer. The future direction for new algorithms will almost certainly involve the development of fast solvers that employ a scalable partitioning of the problem suitable for parallel computer architectures. The mindset will change from porting existing applications to parallel machines, to designing algorithms that inherently require a scalable partitioning of the problem."